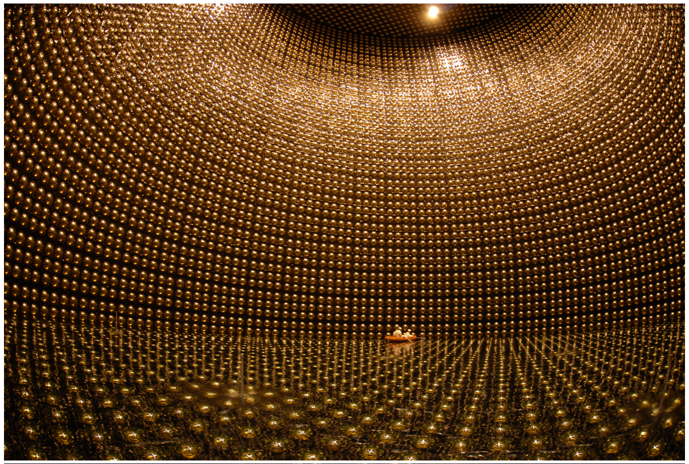
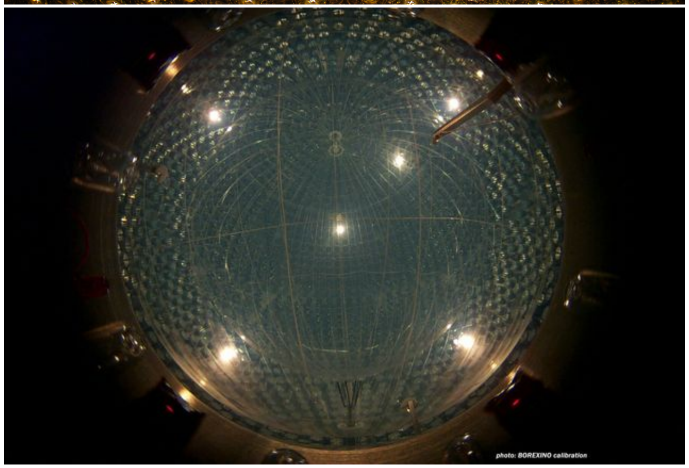
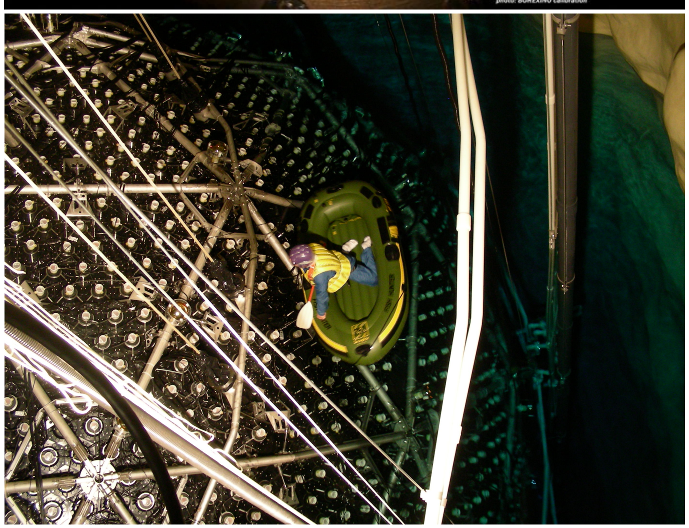





Solar Neutrinos: Status and Prospects

Mark Chen
Queen's University

IV Pontecorvo Neutrino Physics School

These Lectures

- a quasi-historical journey, with flash forward to the present day, looking back at solar neutrino experiments to establish the present day status
  - radiochemical, water Čerenkov, liquid scintillator
- a look at future prospects
  - new experiments being built and what new physics they will explore
  - brief look at some experiments being proposed

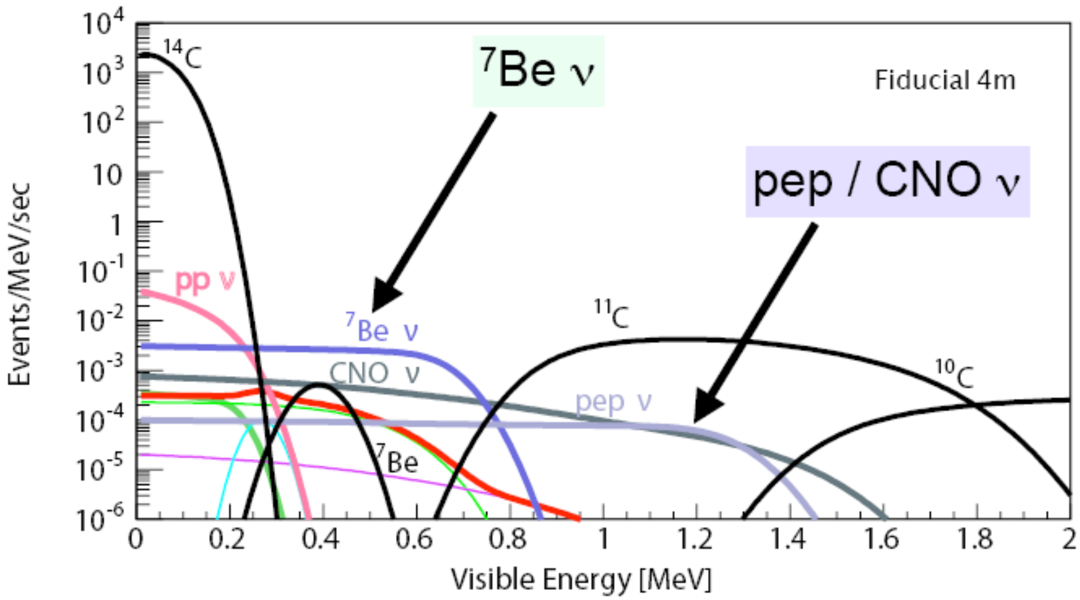
- Note: I have borrowed figures and material from many experiments and many people. Thanks to all of them!

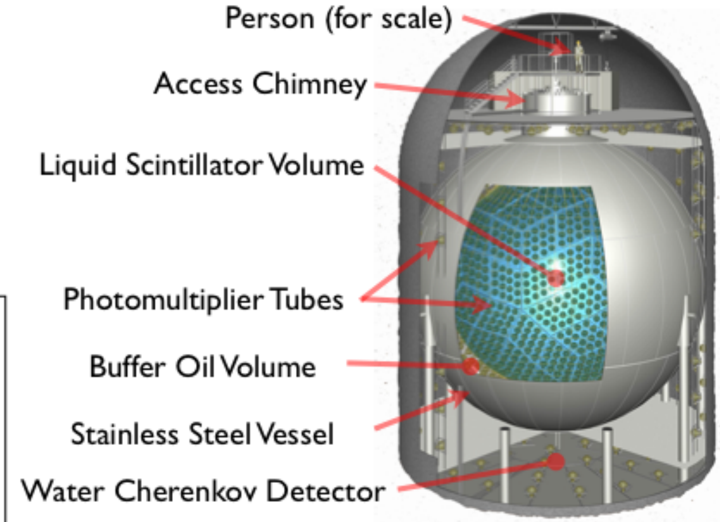
Current, Recent Results

- to discuss future prospects, I will start with an examination of current, recent results and activities

KamLAND

- 1000 tons (80% dodecane, 20% pseudocumene)
- 1880 PMTs (17” and 20”)
  - 34% photocathode coverage
- singles spectrum shows ^{210}Pb and ^{85}Kr and also ^{40}K contamination





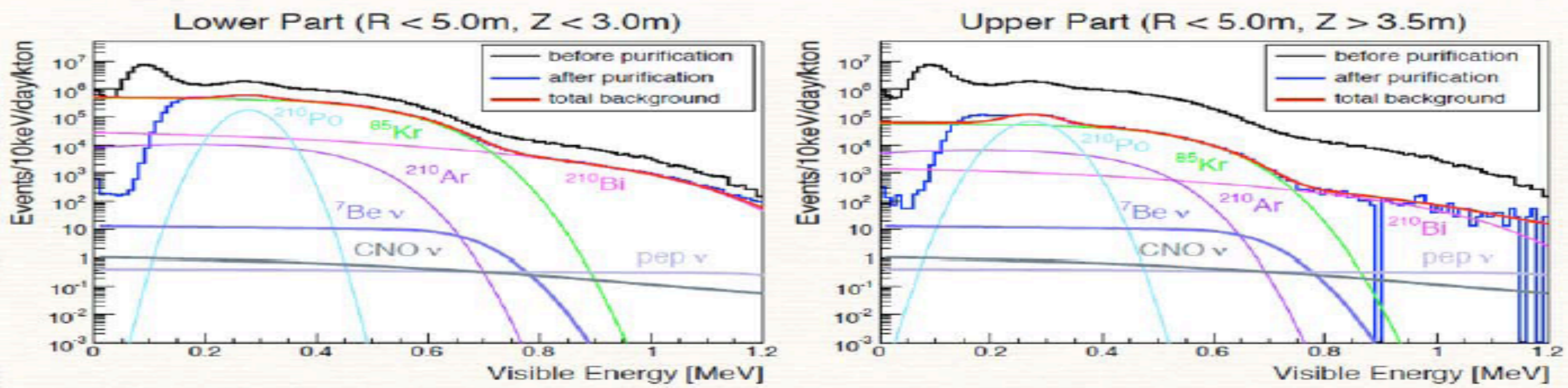
must purify liquid scintillator to achieve solar ν sensitivity

goal: 10^5 to 10^6 reduction

KamLAND Purification Status

- 1st purification campaign: 2007-05-12 to 2007-08-01
  - purified 1500 m^3, some reduction seen

	^{210}Bi	^{85}Kr	^{39}Ar	^{210}Po	^{40}K
Before	42^{+8}_{-6}	508^{+19}_{-34}	18^{+38}_{-18}	43^{+1}_{-2}	44±4μBq/m^3
After (top) (low)	0.2±0.1 10±1	14^{+1}_{-4} 185^{+1}_{-2}	0^{+5}_{-0} 0^{+2}_{-0}	9±1 14±1	- 13±1μBq/m^3
Reduction (top) (low)	$(4.8\pm2.6)\times10^{-3}$ 0.24±0.05	$(2.8\pm0.8)\times10^{-2}$ 0.36±0.02	- -	0.21±0.03 0.33±0.03	- 0.29±0.03



- 2nd purification campaign: 2008-06-16 to 2009-02-06
  - three full volumes purified, 10^4 to 10^5 reduction seen

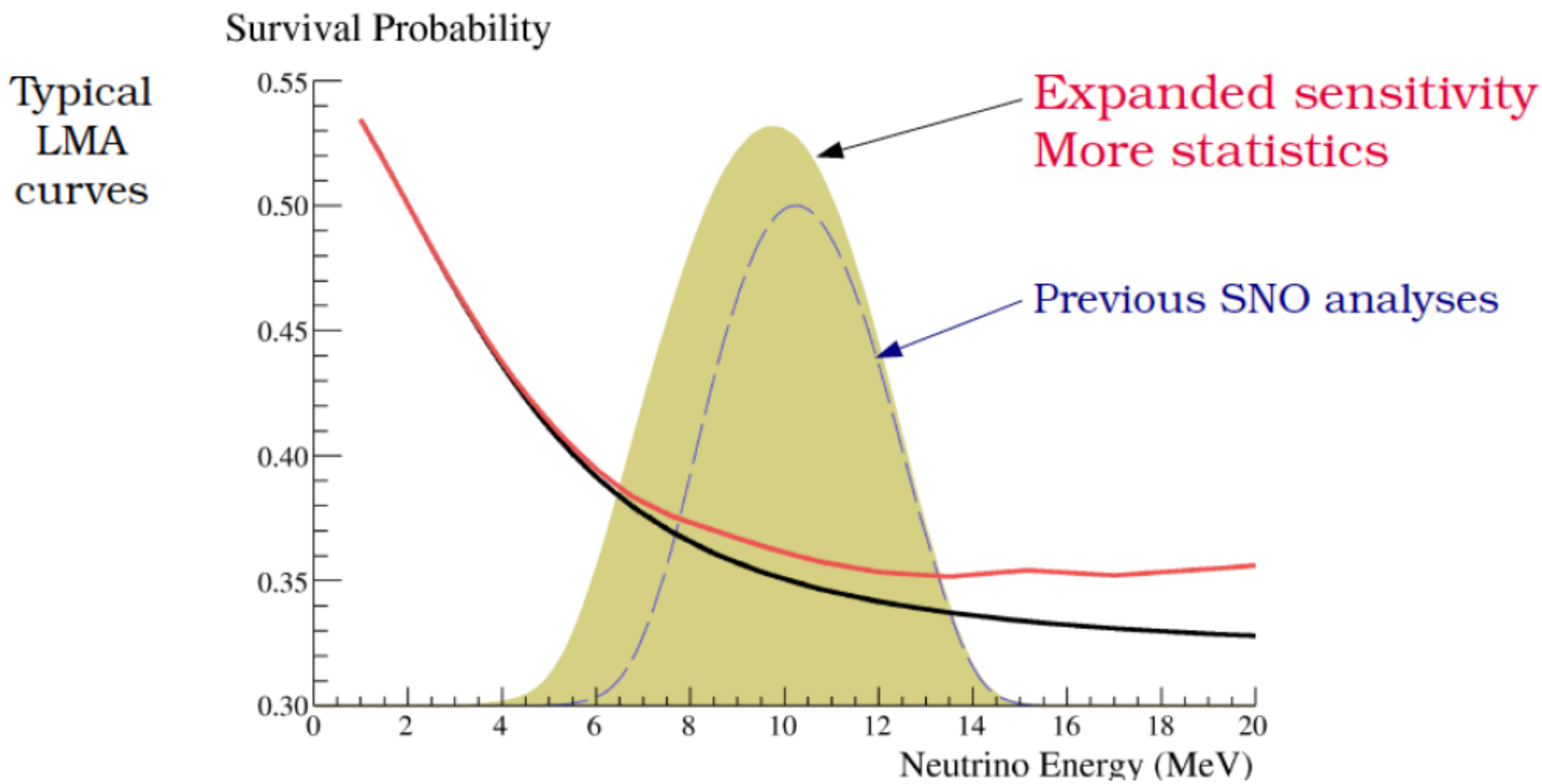
New SNO Results

Physical Review C **81**, 055504 (2010)

- lower energy threshold analysis (LETA)
- combined Phase I+II joint fit
  - signal extraction in each phase helps constrain the other
  - improvement is better than just simple statistical combination
- improved simulations and analysis (e.g. energy resolution is slightly better helping suppress steep background tails)
- reduced systematic uncertainties
- different signal extraction techniques
- improved oscillation analysis

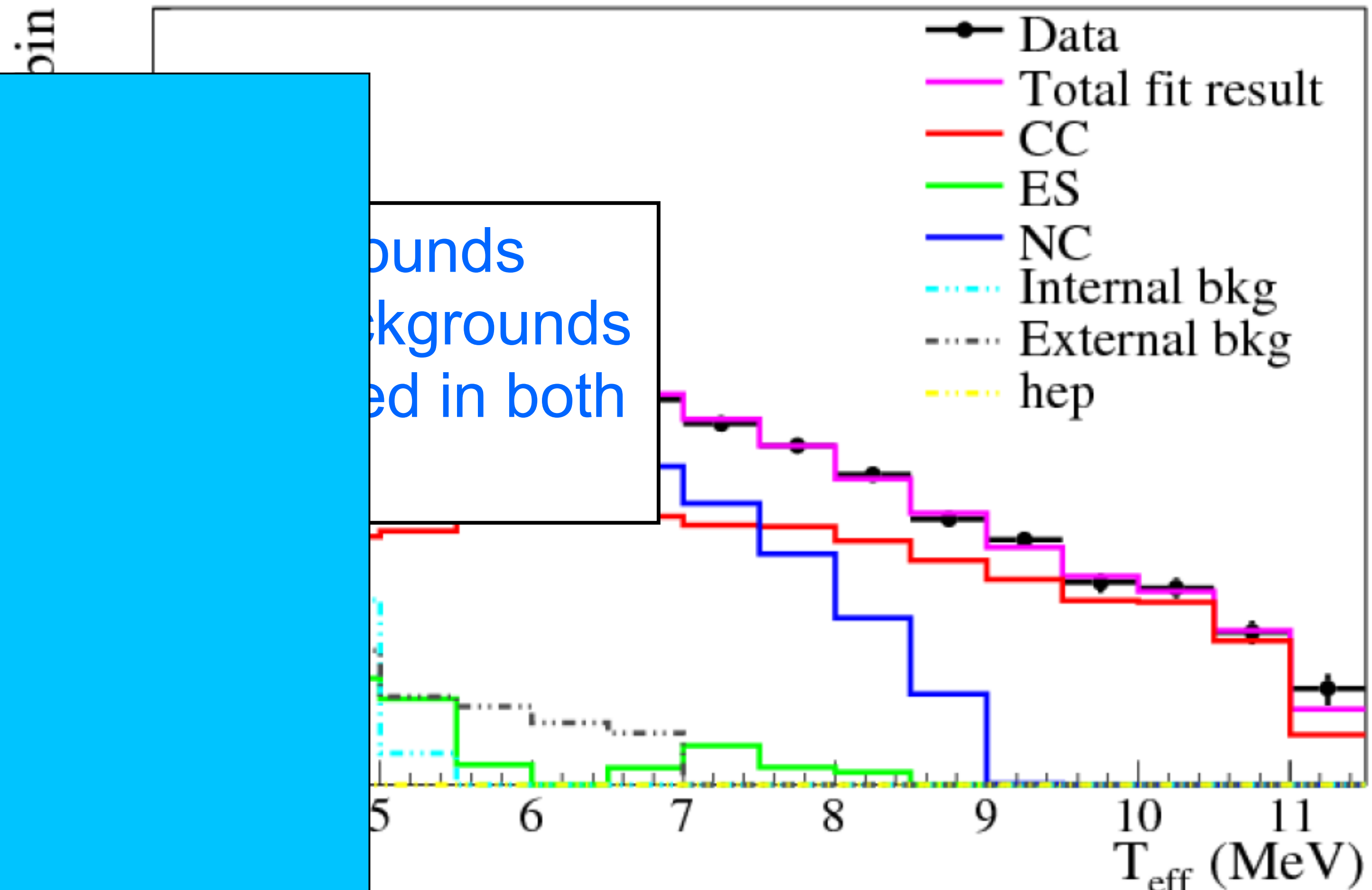
From 5 → 3.5 MeV Analysis Threshold

CC statistics



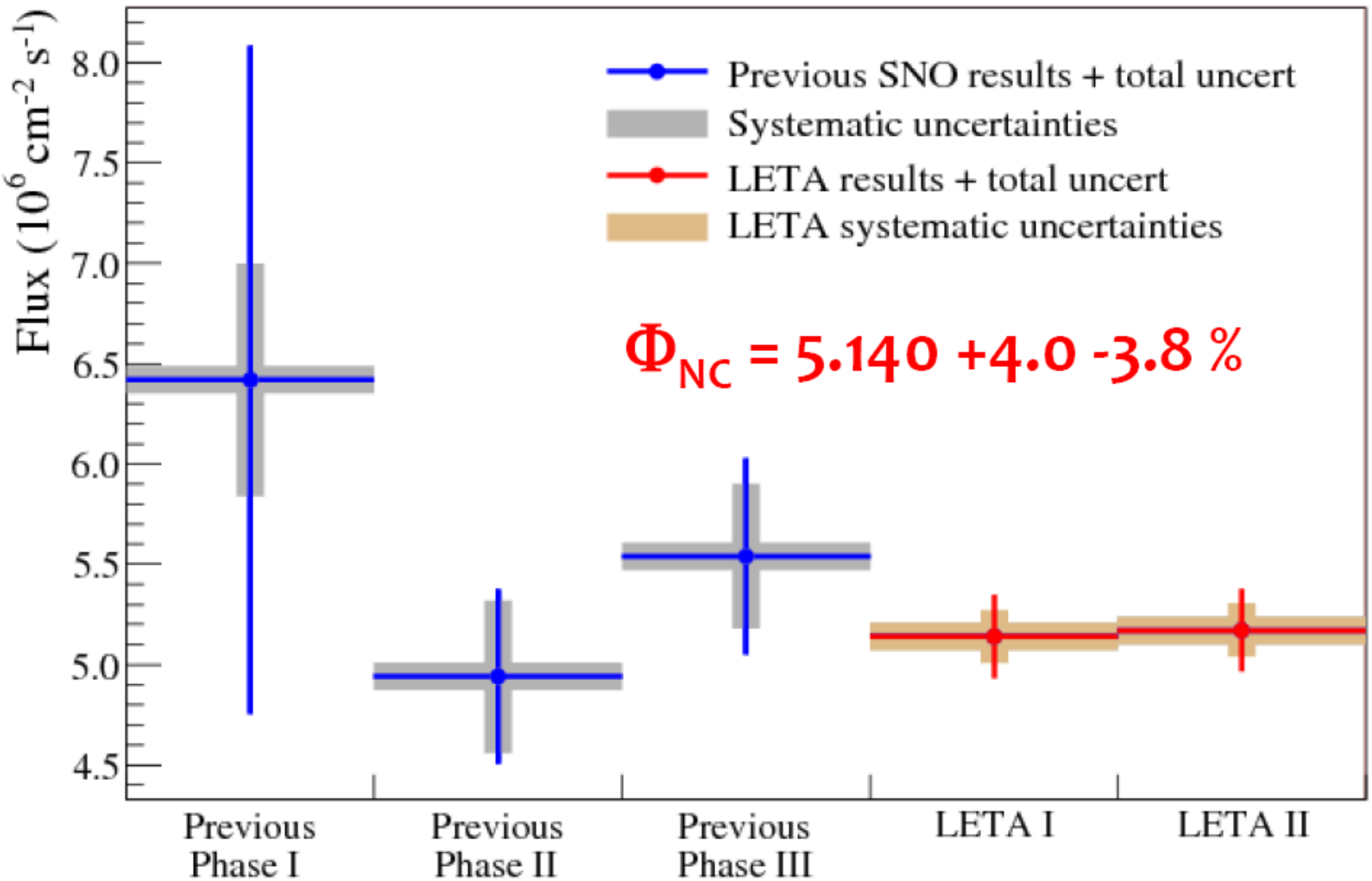
Extracted Spectrum (Signals and Background)

$\boxed{\chi^2 = 13.6 / 16}$ Fit Result



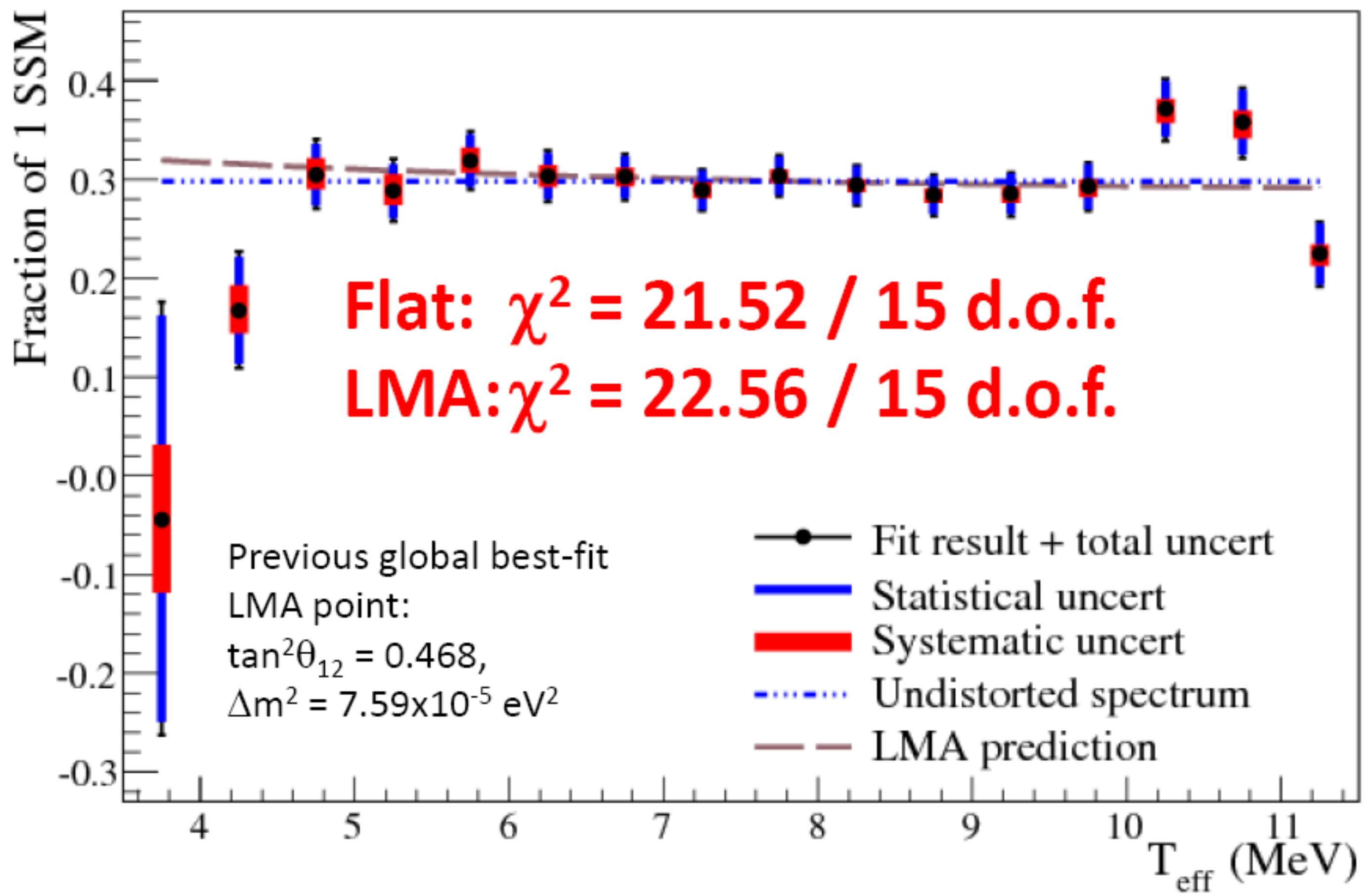
5 i ... ounds
+ ... ckgrounds
we ... ed in both
Ph ...

New SNO Low Energy Threshold Analysis
^{8}B Solar Neutrino Flux Measurements

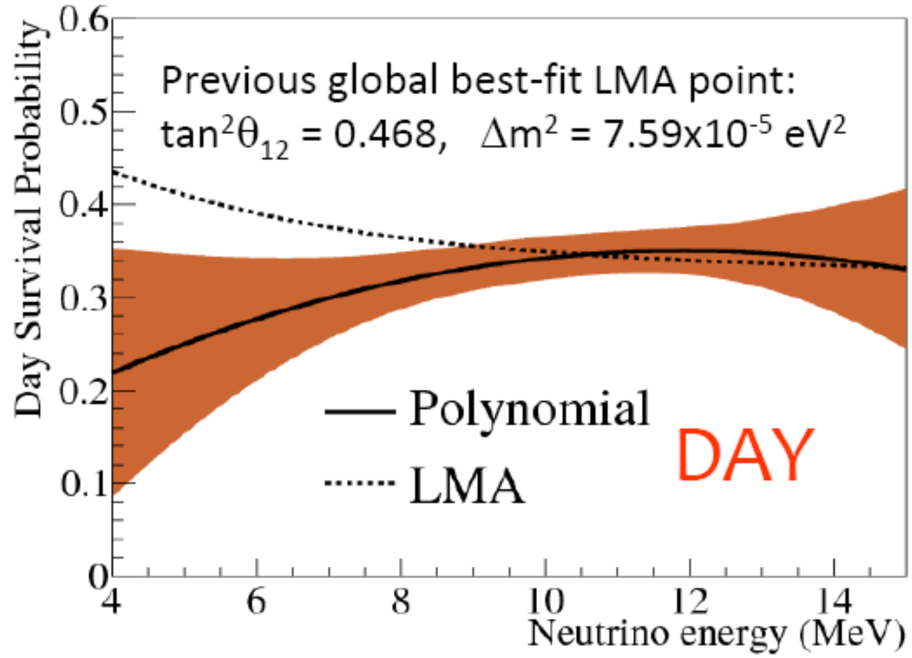


Spectrum from CC Events

CC Recoil-Electron Spectrum



Direct Fit for Energy-Dependent Survival Probability

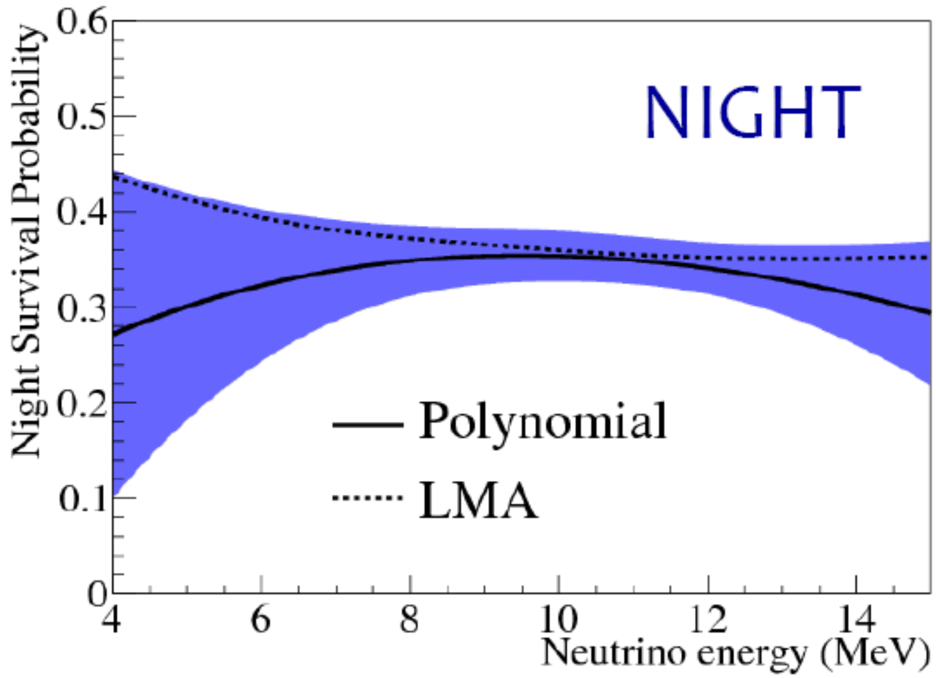


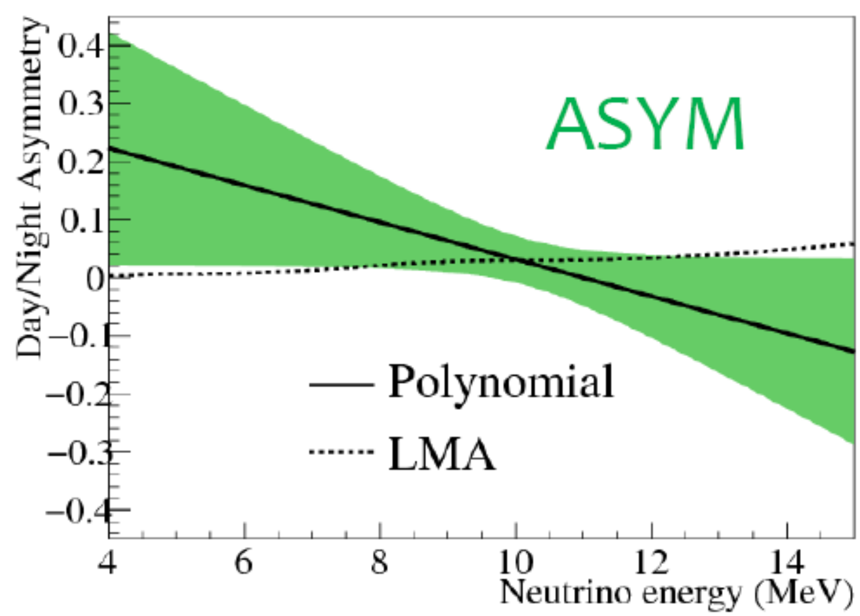
No distortion, no a/s:

$\Delta\chi^2 = 1.94$ / 4 d.o.f.

LMA-prediction:

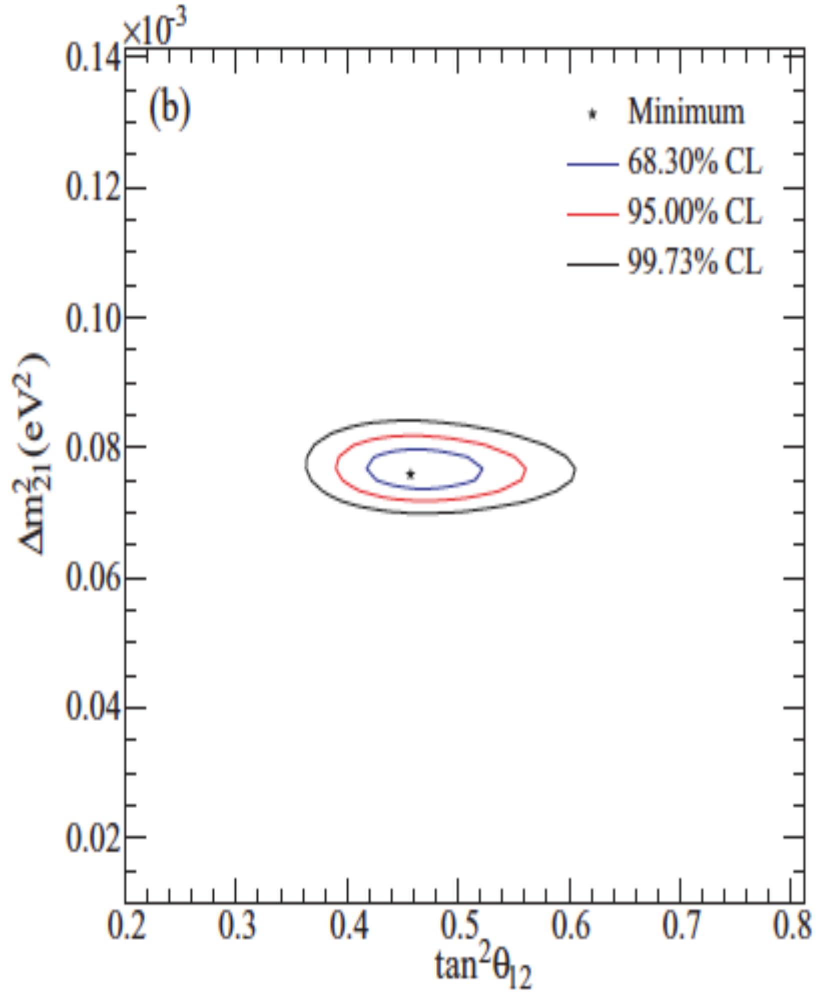
$\Delta\chi^2 = 3.90$ / 4 d.o.f.





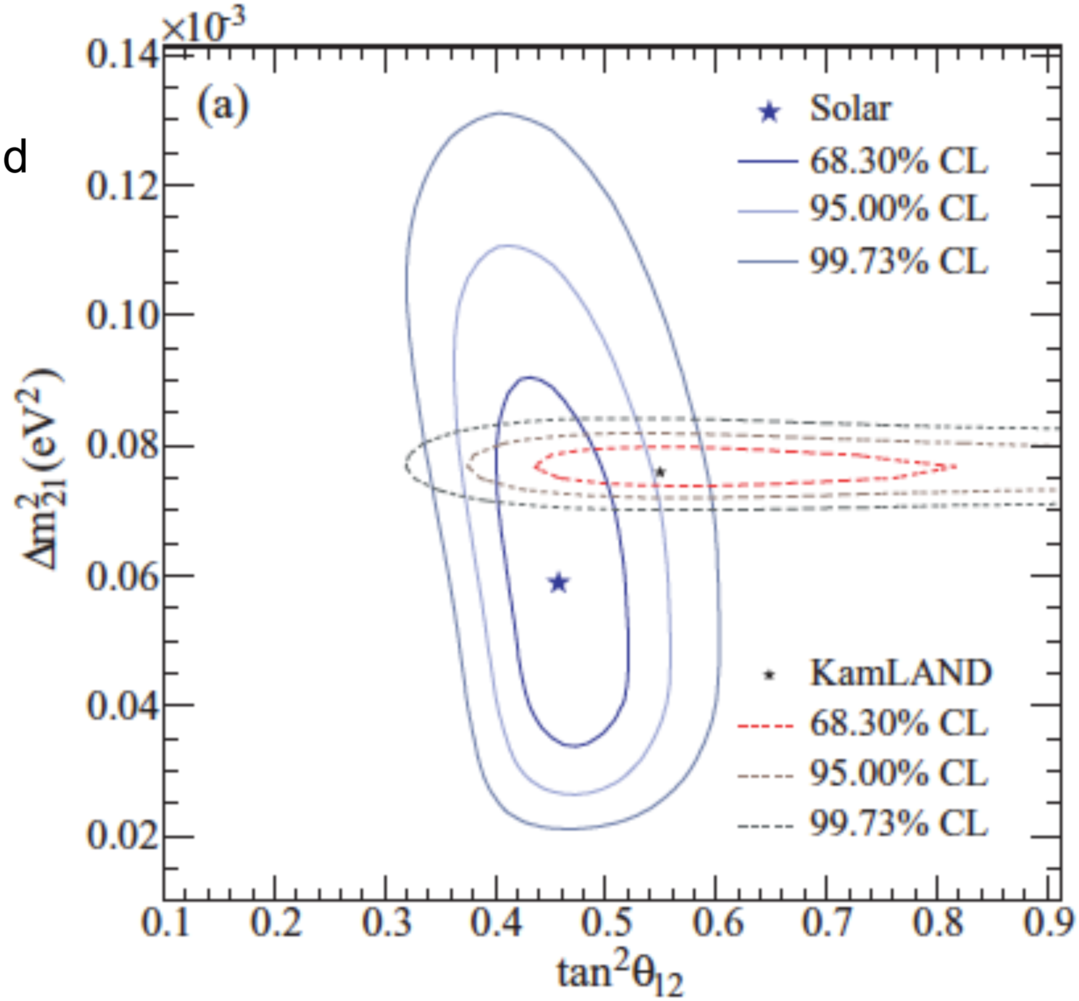
New SNO Paper has a 3-Neutrino Oscillation Analysis

global solar plus KamLAND



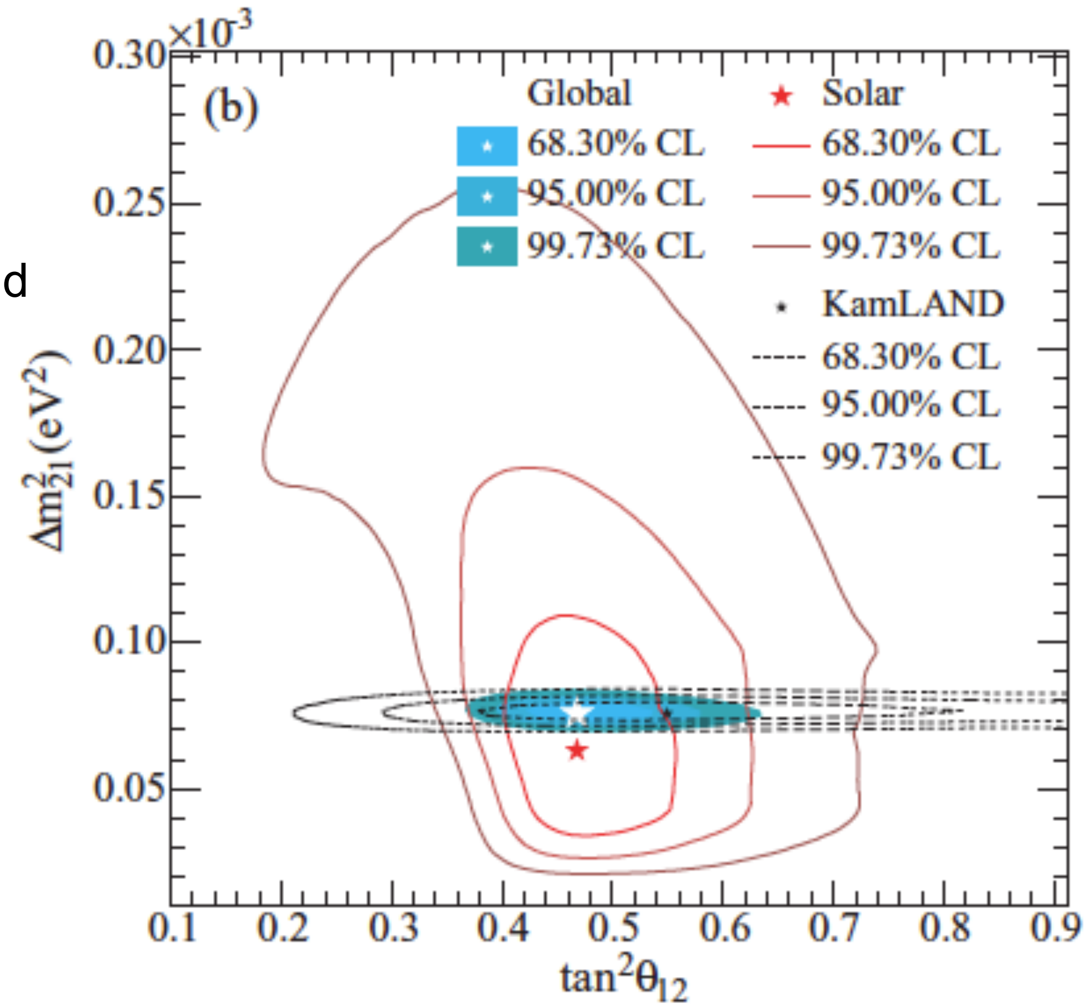
New SNO Paper has a 3-Neutrino Oscillation Analysis

global solar and KamLAND separately



Solar + KamLAND 3-Neutrino Overlay

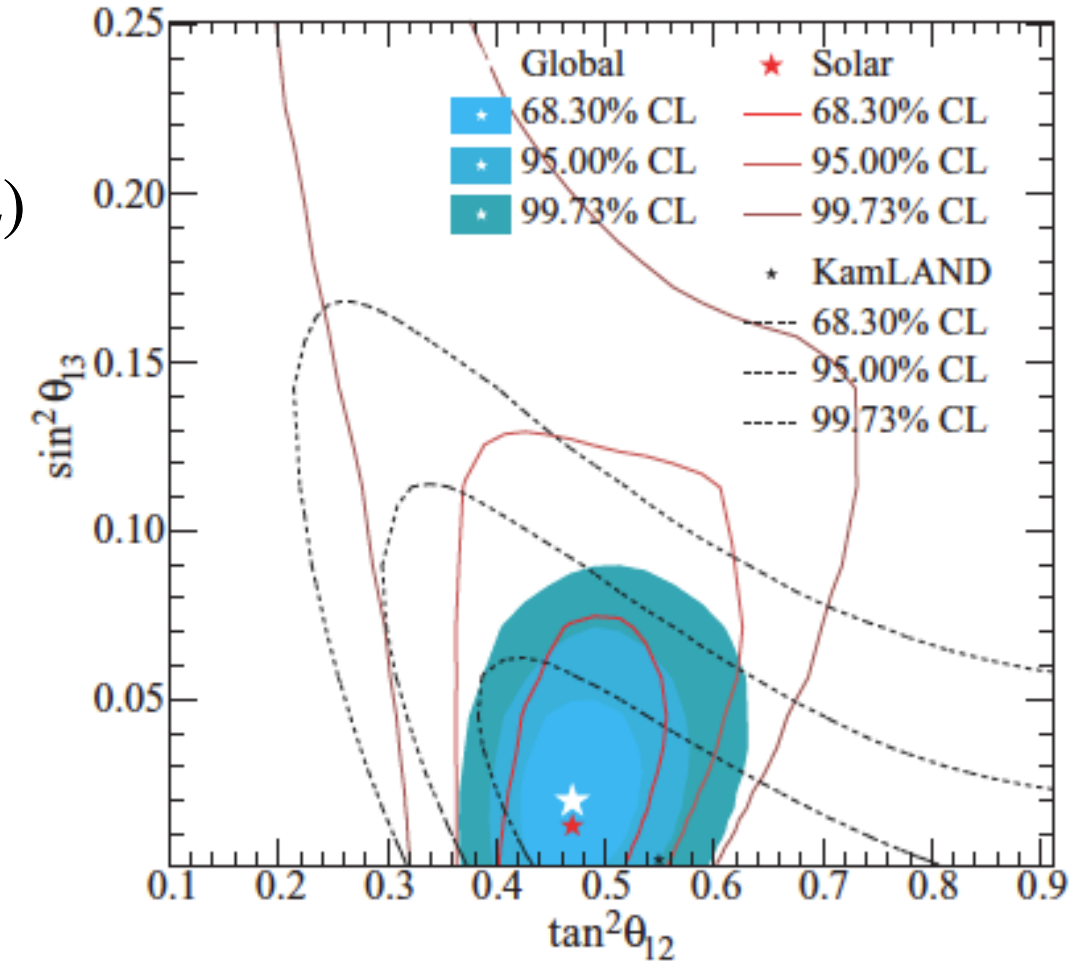
global solar and KamLAND separately



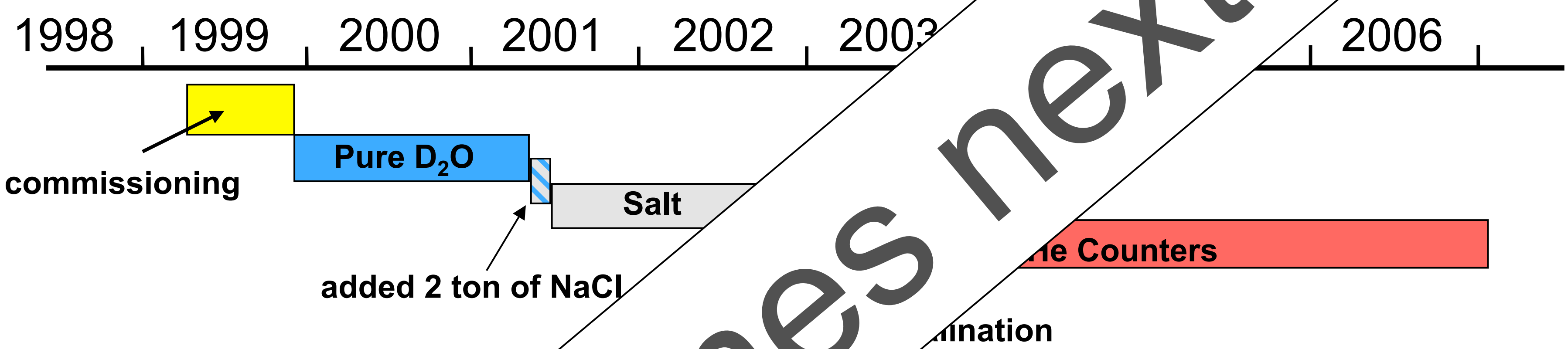
Solar + KamLAND 3-Neutrino Overlay

$$\sin^2\theta_{13} = 2.00^{+2.09}_{-1.63} \times 10^{-2}$$

$$\sin^2\theta_{13} < 0.057\,(95\%\ \mathrm{CL})$$



SNO Timeline Summary



what comes next?

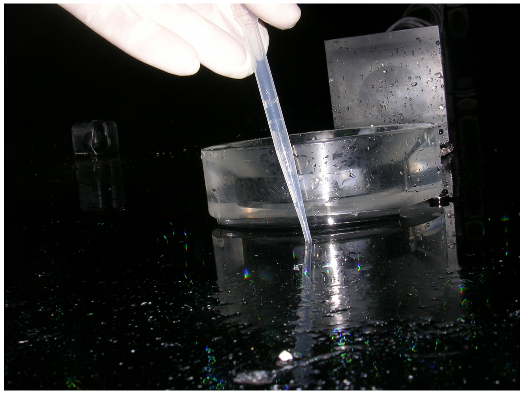
• pure D_2O phase discover … trino flavors that are not ν_e

• salt phase moved o … mination of oscillation parameters; flux determination had … aint (thus could use it rigorously for more than just the n … – day/night effect and spectral shape were studied as … ve ^8B solar neutrino flux

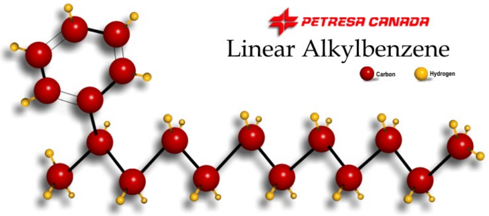
• Pha … offered CC and NC event-by-event separation, for imp … nd cleaner spectral shape examination; analyses combining all thr … re in progress

SNO+

- $300M of heavy water removed and returned to Atomic Energy of Canada Limited (every last drop)
- SNO detector to be filled with liquid scintillator
  - 50-100 times more light than Čerenkov



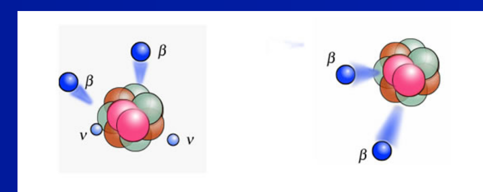
- linear alkylbenzene (LAB)
  - compatible with acrylic, undiluted
  - high light yield, long attenuation length
  - safe: high flash point, low toxicity
  - cheaper than other scintillators

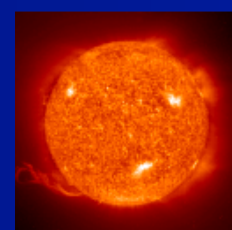


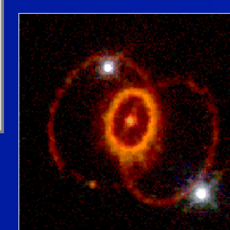
- physics goals: *pep* and *CNO* solar neutrinos, geo neutrinos, reactor neutrino oscillations, supernova neutrinos, double beta decay with Nd

SNO+ Physics Program

- search for neutrinoless double beta decay
- neutrino physics
  - – solar neutrinos
  - – geo antineutrinos
  - – reactor antineutrinos
  - – supernova neutrinos



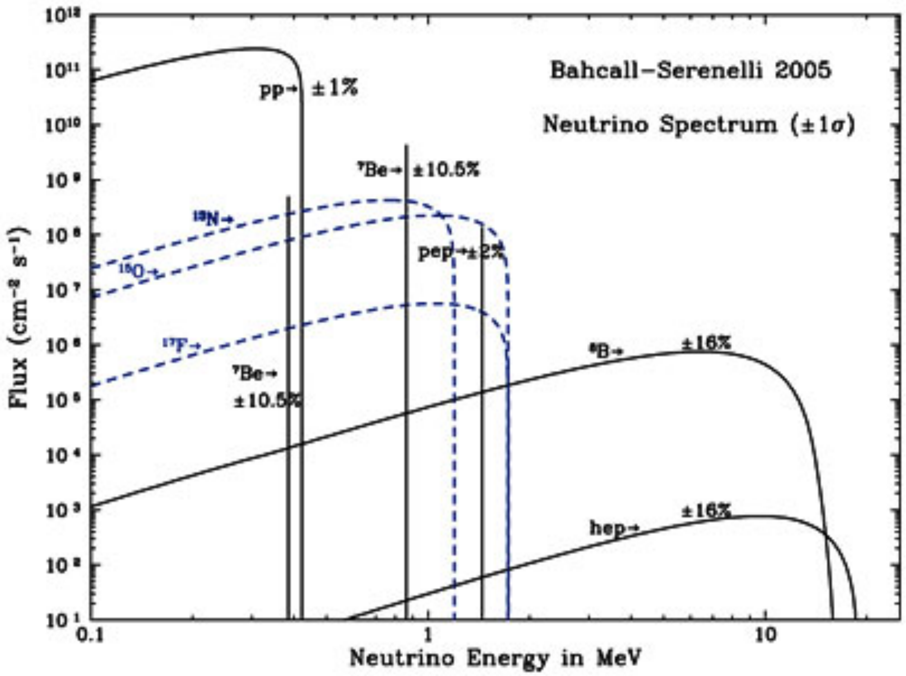




SNO+ Physics Goals

Solar Neutrinos: What's Known
Putting It All Together

- ^{8}B solar ν well studied
  - by Super-K and SNO
- there are good data on *pp* solar ν's from the Ga experiments
  - must determine contribution of ^{8}B and ^{7}Be, subtract, and you get *pp* from the Ga experiments
- Borexino has measured the ^{7}Be flux



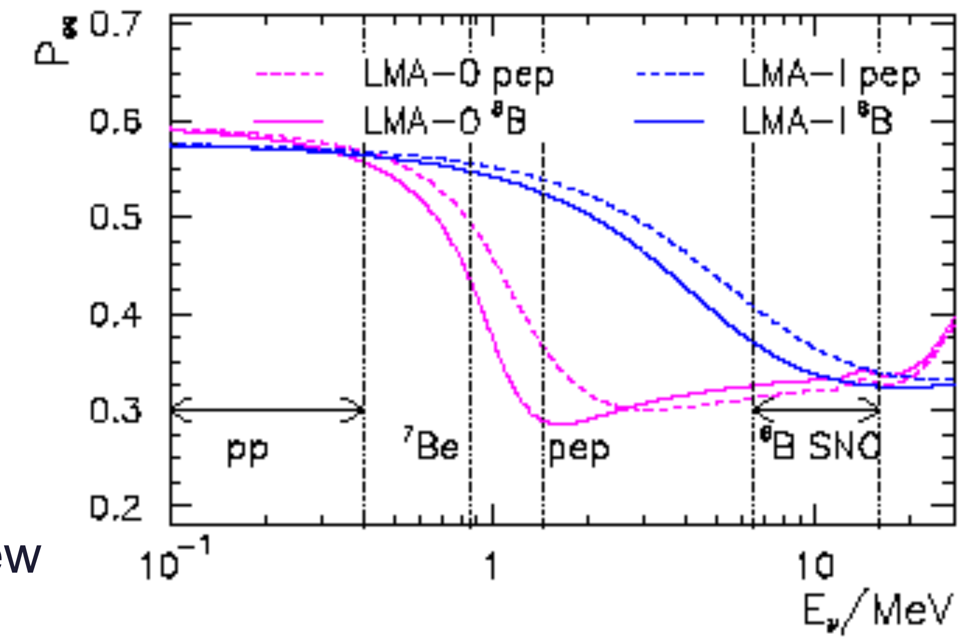
***pep* and *CNO* solar neutrinos are the next targets and SNO+ aims to detect these**

Neutrino-Matter Interaction

- exploring the vacuum-matter transition is sensitive to new physics
- new neutrino-matter couplings (either FCNC or lepton universality violating) can be parameterized by a new "MSW" term ε
- where is the relative effect of new physics the largest?
  - at resonance!
- for $\Delta m^2 = 8 \times 10^{-5}$ eV^2, $\theta = 34°$ N_e at the centre of the Sun → E is 1-2 MeV

***pep* solar neutrinos → good place to look for new physics**

P_{ee} curve with non-standard interactions

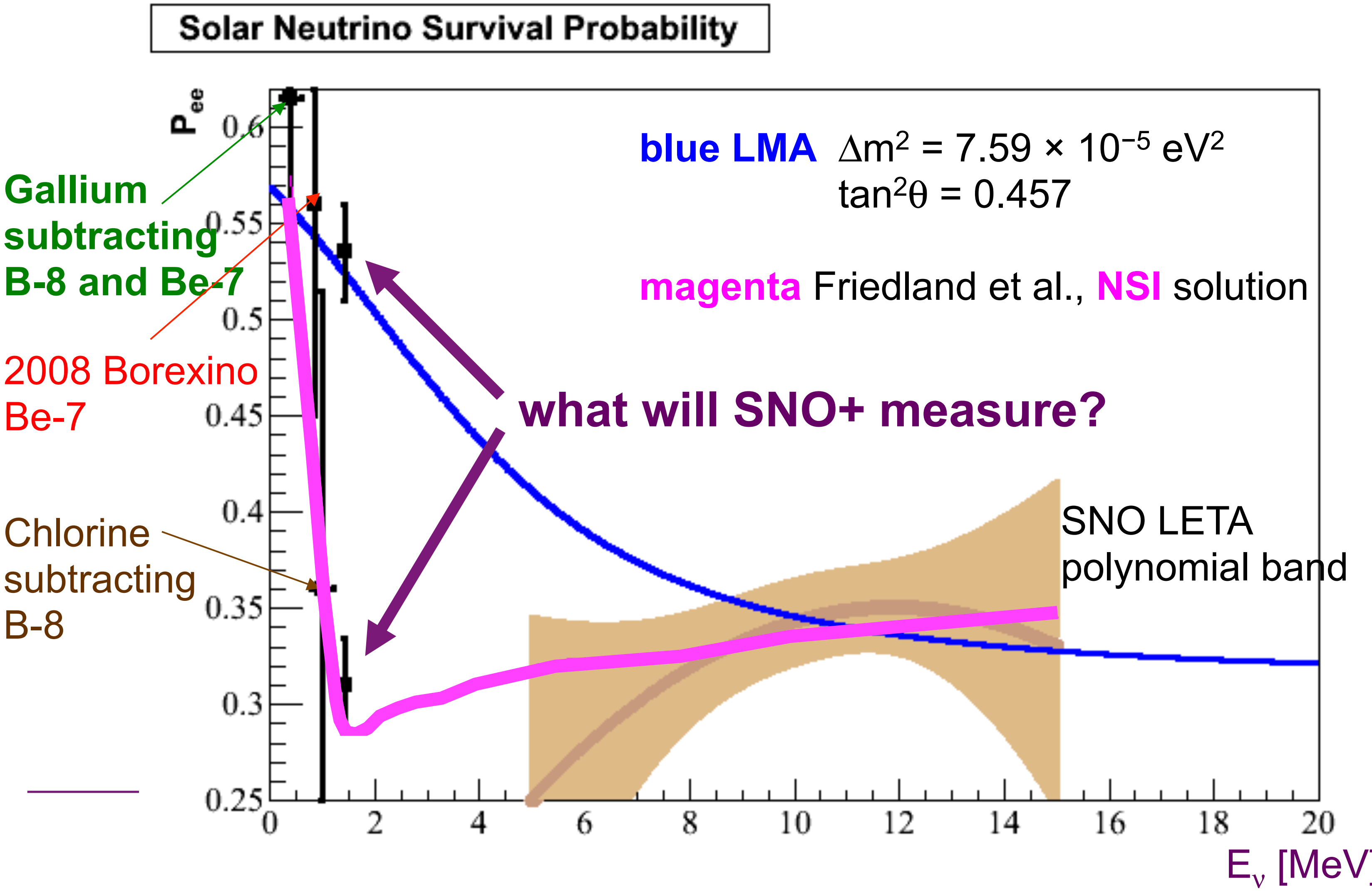


from Friedland, Lunardini, Peña-Garay, hep-ph/0402266

$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}\,G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

Hamiltonian for neutrino propagation in the Sun

Survival Probability for Solar Neutrinos: All Experimental Data Distilled



Borexino Has Detected ^{8}B Solar Neutrinos

arXiv:0808.2868v2

- lowest energy bin seems low also!

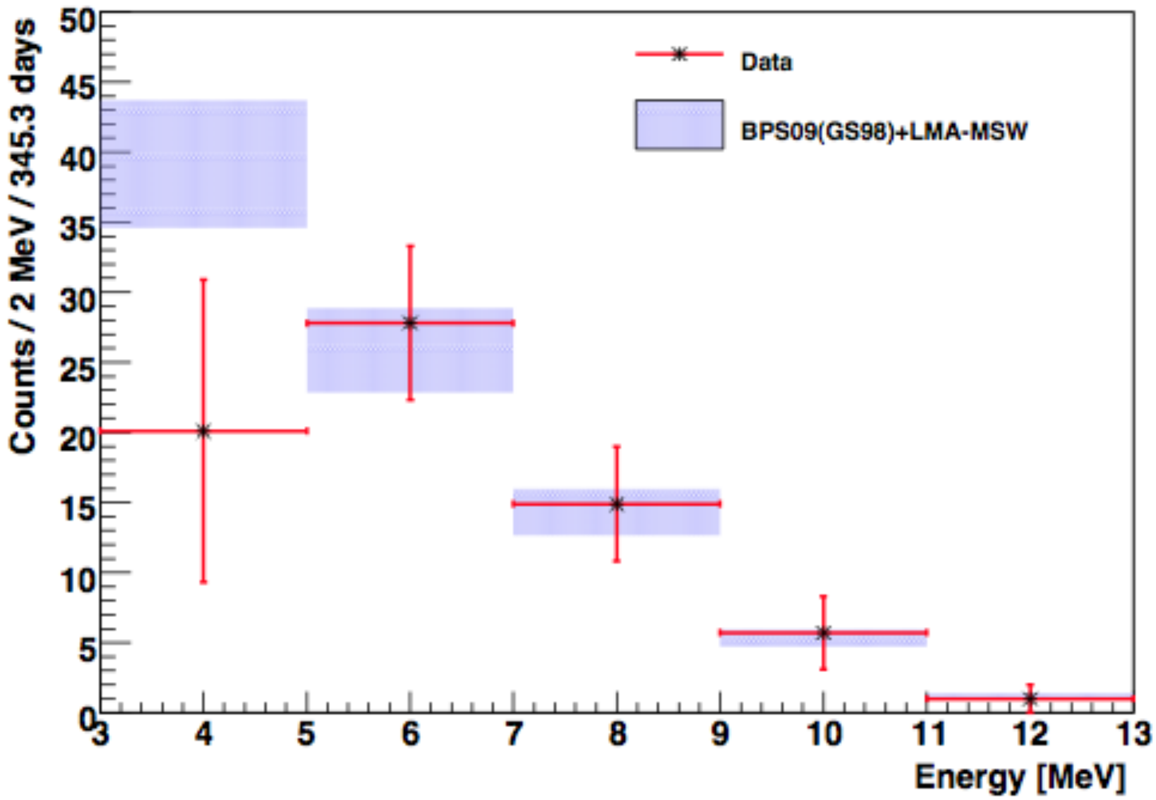
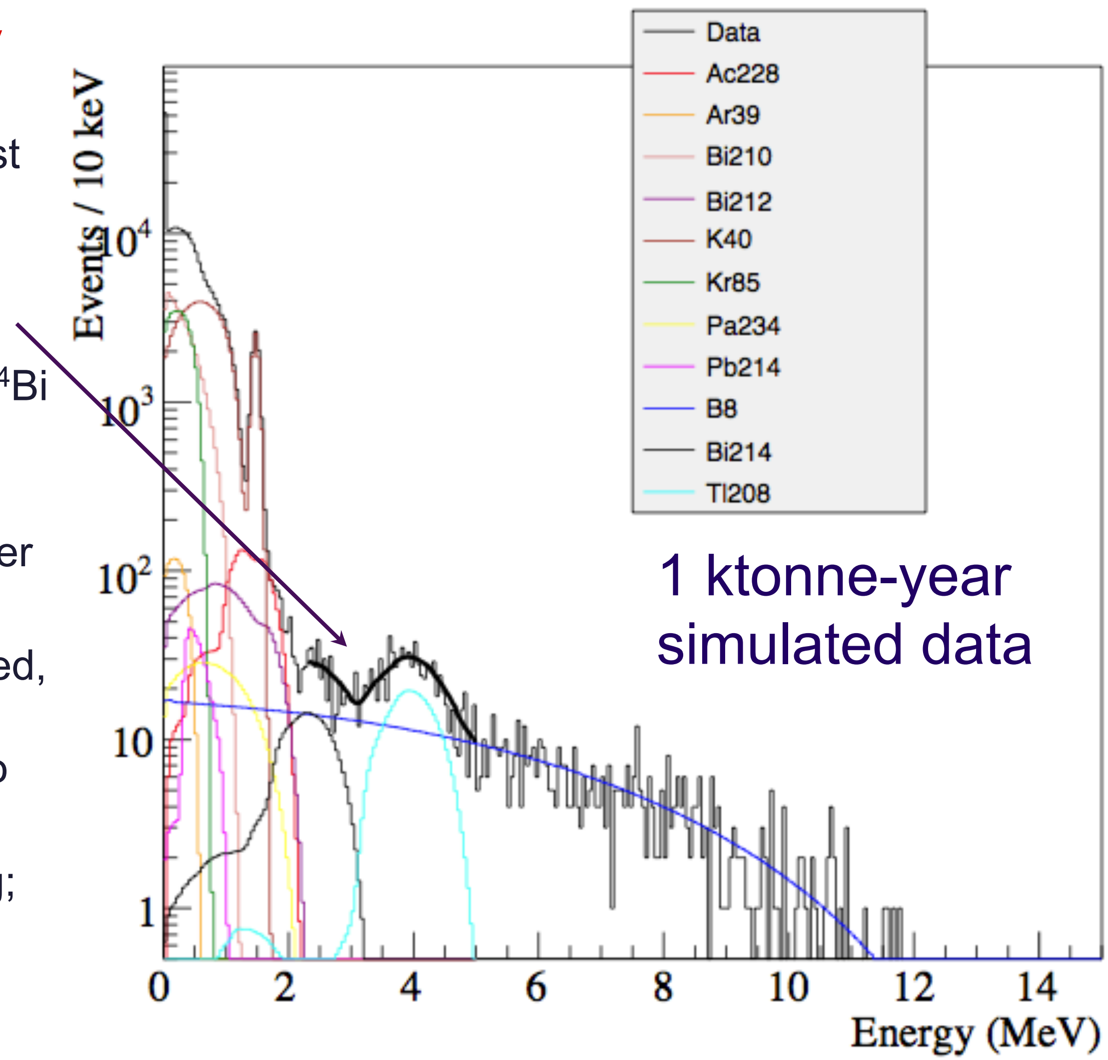


Figure 7: Comparison of the final spectrum after data selection and background subtraction (red dots) to Monte Carlo simulations (blue) of oscillated ^{8}B ν interactions, with amplitude from the Standard Solar Model BPS09(GS98)

SNO+ Lower Energy ^8B Solar Neutrinos

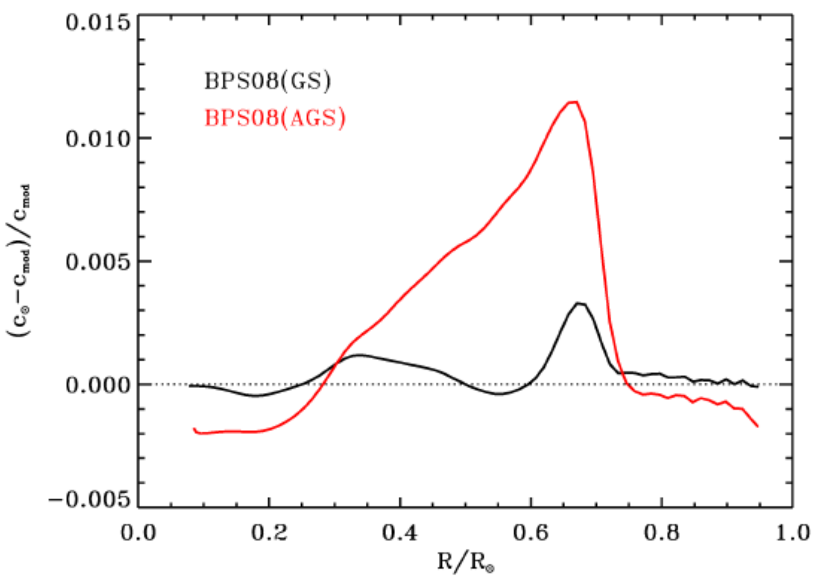
- SNO+ can also detect lower energy ^8B solar neutrinos
- cosmogenic backgrounds are lowest in SNO+
  - compared to KamLAND and Borexino
- low background pocket between ^{214}Bi (radon in the U chain) and ^{208}Tl (internal Th chain contamination)
  - will give a data point with smaller uncertainties
  - ^{214}Bi backgrounds can be tagged, cut by delayed coincidence (haven't included in this plot, so real data will be better)
  - ^{208}Tl backgrounds harder to tag; but, if can't tag, still use to constrain via ^{212}Bi-^{212}Po coincidence



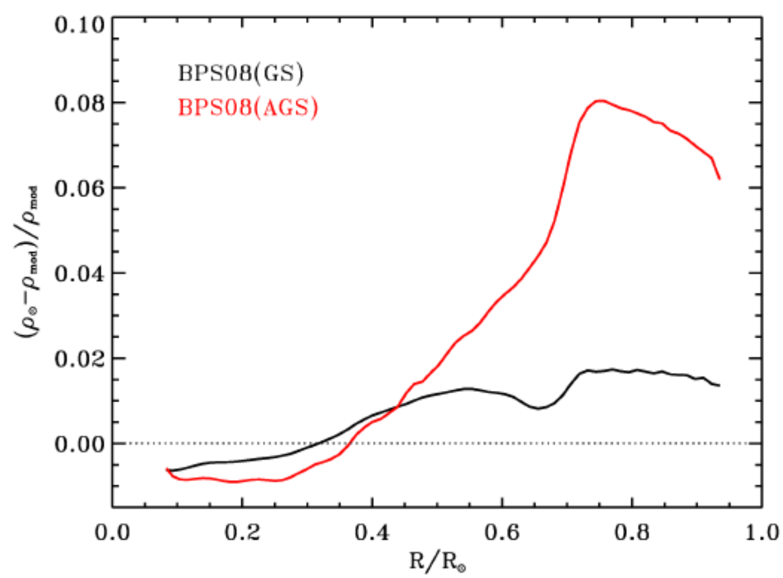
Helioseismology and Solar Metallicity
A New Problem with Solar Models

- Asplund, Grevesse and Sauval determined new solar chemical abundances (metallicity) in 2005 using improved 3D hydrodynamical modeling (tested with many surface spectroscopic observations)
- with these new chemical abundances in solar models (lower metallicity), the previous excellent agreement between model calculations and helioseismology is broken

new C, N, O, Ne abundances lower by 30-50%



sound speed profile in the Sun



density profile in the Sun

Other Broken Solar Model Predictions

- depth of solar convective zone
- surface helium abundance

helioseismology measurements

$$\frac{R_{\rm CZ}}{R_\odot} = 0.728(0.713 \pm 0.001,\ \text{exp.})$$

$$Y_{\rm surf} = 0.229(0.249 \pm 0.003,\ \text{exp.})$$

☹ solar model prediction with new composition

☺ solar model with old composition: 0.715 and 0.244

Key Assumption of the Solar Model

- evolution from zero age along the main sequence constrained by: initial mass, present luminosity, radius, initial composition with
- initial core metallicity fixed to today's surface abundance (i.e. no change from proto-Sun to now, over 4.6 Gyr)
- solar model assumes the Sun is homogeneously mixed, no substantial mass loss or accretion
- *but maybe solar core metallicity is different than at the surface?*
  - mechanisms have been suggested (e.g. by Haxton, that metal depletion during planet formation and late stage accretion on the solar surface causes surface metallicity to be lower)

use solar neutrinos to look into the solar core (as originally intended!)

Use Solar Neutrinos to Resolve

Source	Hi-Z BPS08(GS)	Lo-Z BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1 \,^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1 \,^{+0.17}_{-0.16})$	$1.34(1 \,^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1 \,^{+0.19}_{-0.17})$	$3.25(1 \,^{+0.16}_{-0.15})$	44%
Cl	$8.46^{+0.87}_{-0.88}$	$6.86^{+0.69}_{-0.70}$	
Ga	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

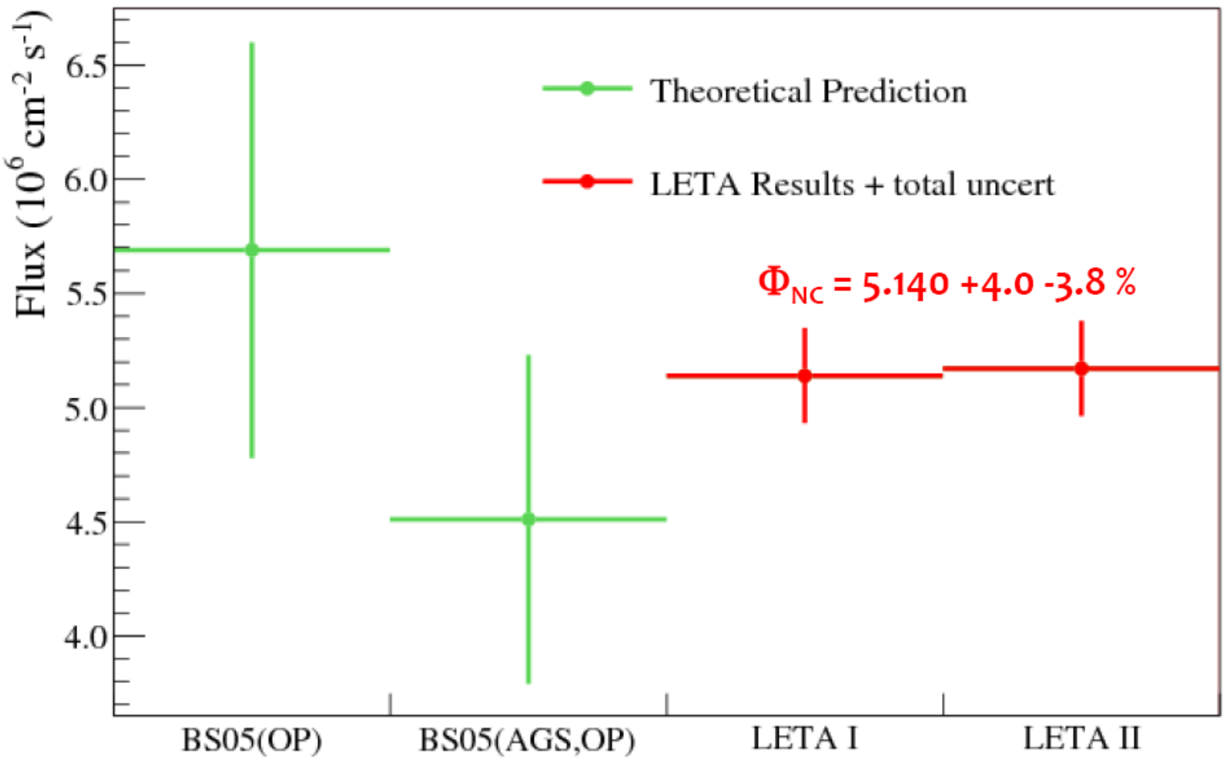
low Z changes core T

directly related to core C, N, O content

BPS08 solar model: Peña-Garay and Serenelli, arXiv:0811.2424

Solar Metallicity and ^{8}B Flux

^{8}B Flux Result

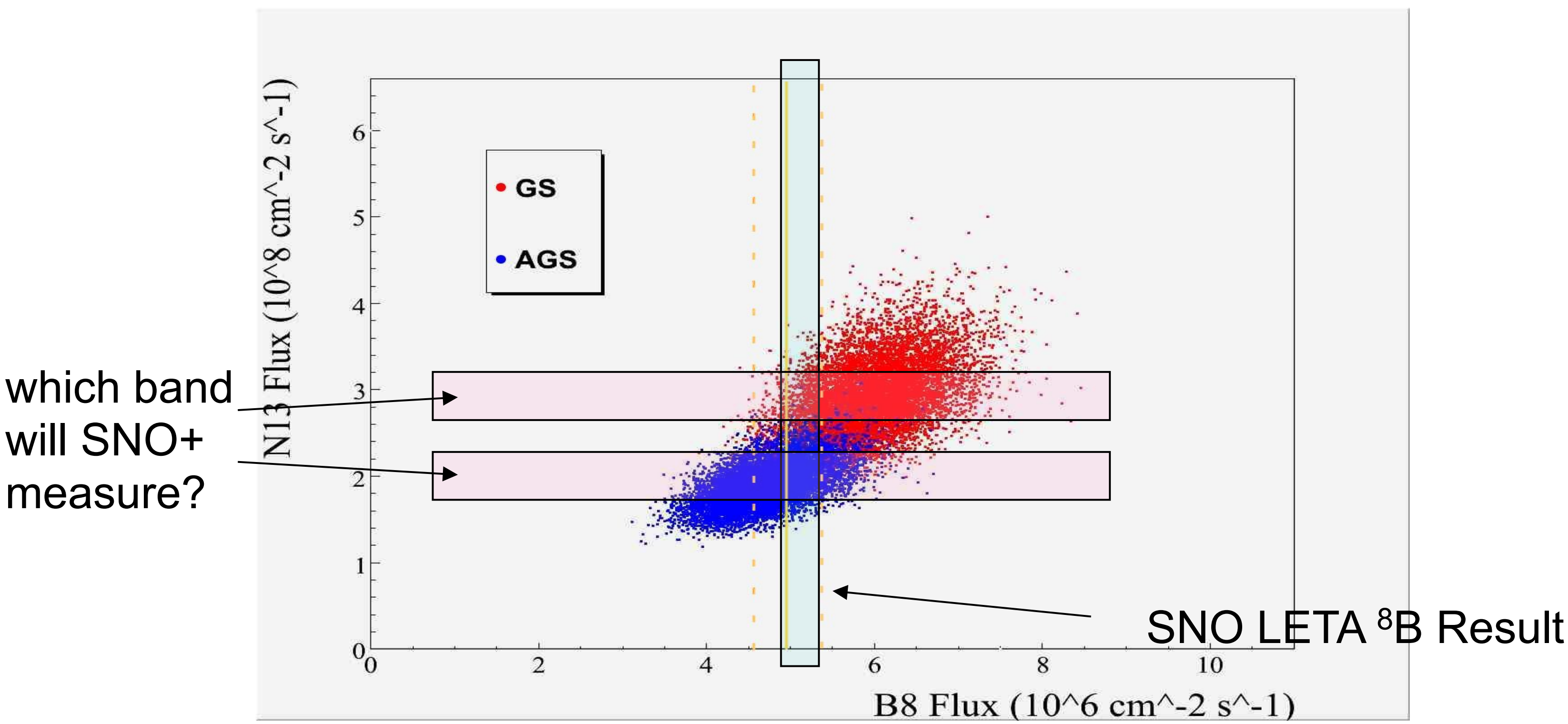


J. N. Bahcall, A. M. Serenelli, and S. Basu, AstroPhys. J. **621**, L85 (2005)

SNO+ CNO and SNO ^{8}B

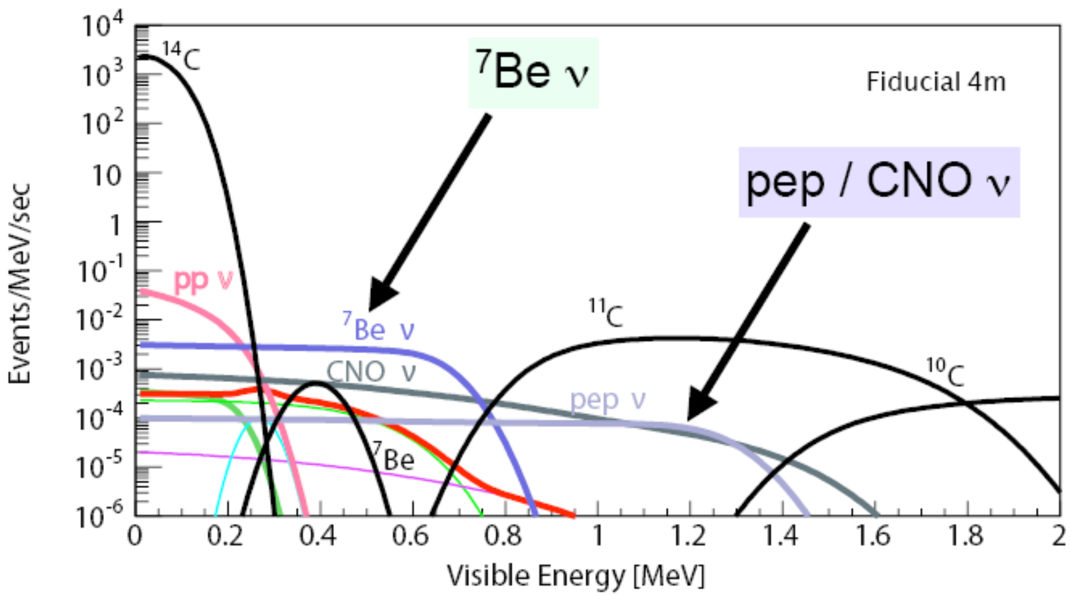
à la Haxton and Serenelli

- use the SNO ^{8}B measurement to constrain “environmental variables” in the solar core which also affects CNO ν
- measure CNO flux (to ±10%) and compare with solar models to differentiate high-Z / low-Z core metallicity



Measuring the *pep* and *CNO* Neutrino Flux

- underground cosmogenic background from ^{11}C is eliminated at SNOLAB depths of 6000 mwe
  - muon flux is ~700 times lower than Kamioka, ~100 times lower than Gran Sasso



^{11}C has a 20 min half-life – challenging to veto or tag this background for ~10,000 muons/day

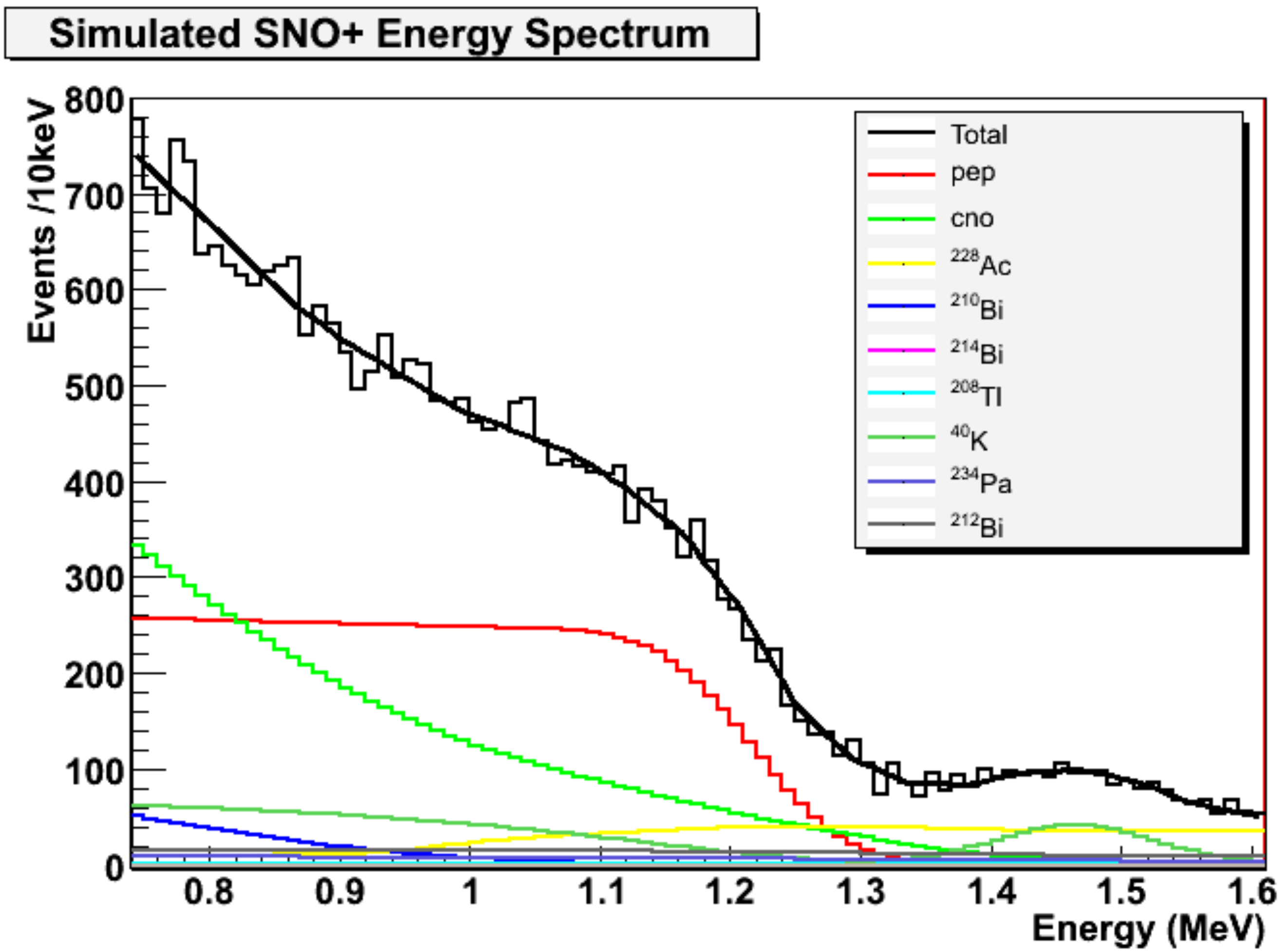
SNO+ will have ~70 muons/day

figure from KamLAND: solar neutrinos in KamLAND and cosmogenic carbon backgrounds

Other Backgrounds to *pep* in SNO+

- radiopurity requirements
  - ^{40}K, ^{210}Bi (Rn daughter) are important
  - ^{85}Kr, ^{210}Po (as seen in KamLAND) not a problem since *pep* signal is at higher energy than ^{7}Be
  - U, Th not a problem if one can duplicate KamLAND or Borexino levels of scintillator radiopurity
- note: Borexino succeeded to fill with little ^{210}Bi contamination by minimizing radon exposure of the scintillator

SNO+ pep and CNO Solar Neutrino Signals



an accurate measurement of the rate of pep solar neutrino interactions:

$R = \Phi P_{ee} \sigma$

flux is calculated in SSM to ±1.5%; cross section is known (ν-e scattering)

➔ yields an accurate measure of the survival probability

CNO measurement uncertainty: ±7% statistical after 3 years

3600 *pep* events/(kton·year), for electron recoils >0.8 MeV

<u>±5% total uncertainty</u> after 3 years (including systematic and SSM)

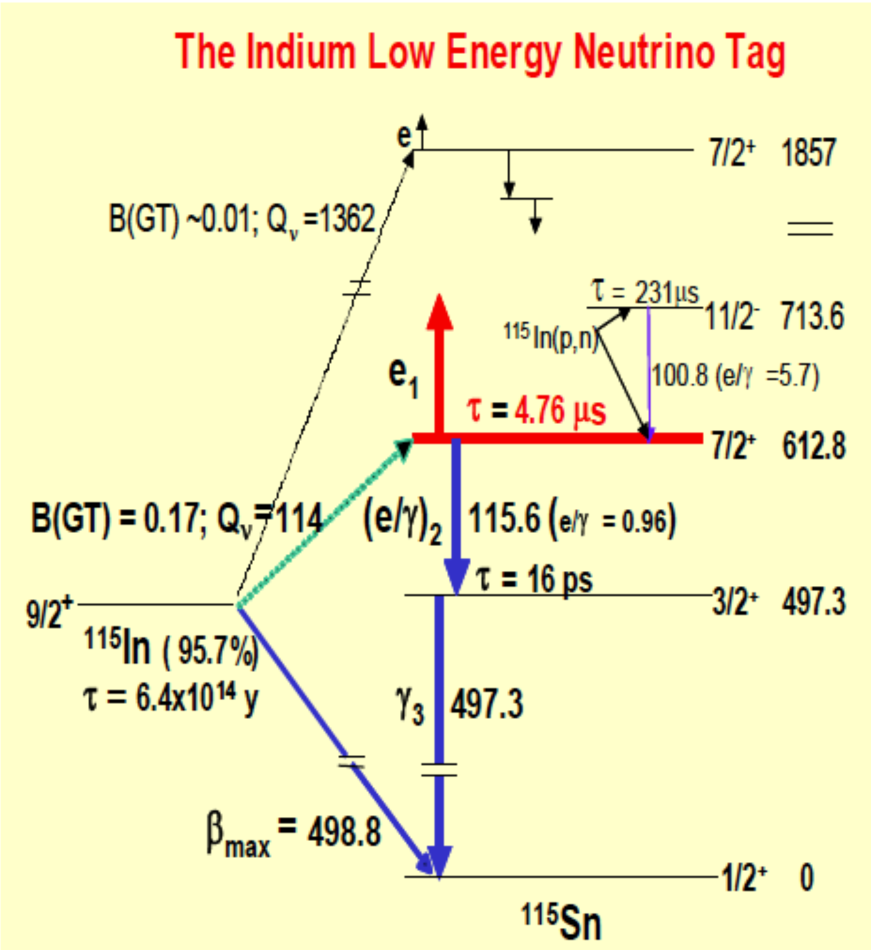
Future Experiments

- charged-current reactions
  - LENS (In) [R&D-prototype] *pp*
  - MOON (Mo) [small-scale R&D] *pp*
- neutrino-electron elastic scattering
  - CLEAN [building DM prototype] *pp*
  - XMASS [building DM prototype] *pp*
  - SNO+ [under construction] *pep+CNO*
  - KamLAND [purified, analyzing data] ^{7}Be

LENS – Low Energy Neutrino Spectroscopy

$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau=4.76\,\mu s)} + {}^{115}Sn$$

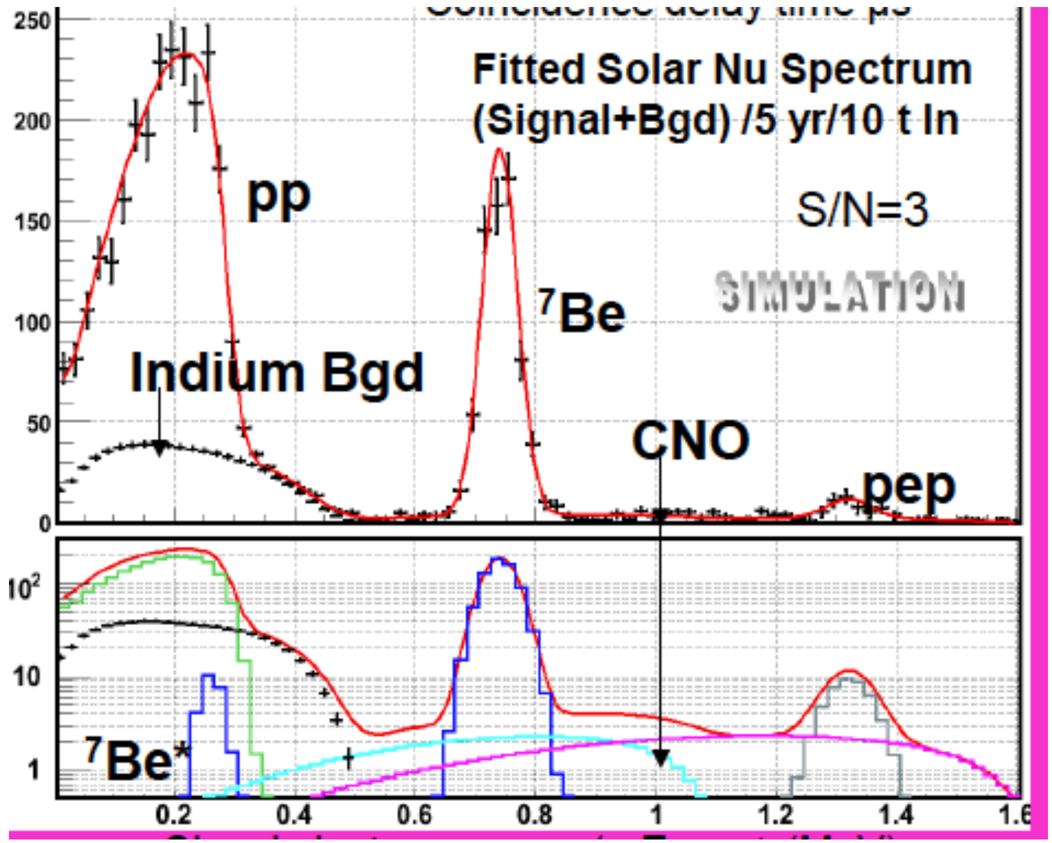
40 *pp* events/(year·ton of In)
includes event tag efficiency



- CC measurement of *pp* flux using an 8% In-loaded scintillator
- suppress ^{115}In β^- background
  - 79×10^{11} backgrounds/(yr·ton of In)
  - use spatial event topology
  - use coincidence time
  - β^- energy <500 keV
  - tagged sum = 613 keV
- requires neutrino source calibration of CC cross section
- MINI-LENS being built: 128 L of scintillator (<1/1000 of LENS)

Tagged Signal → No Backgrounds

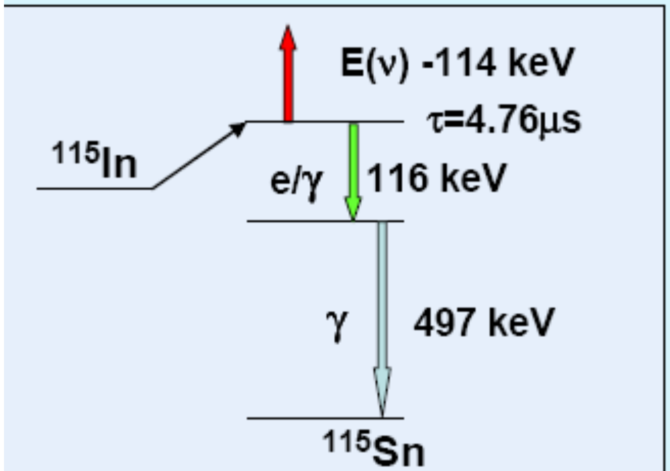
- clean spectroscopy of low energy solar neutrinos
- for 5 yr and 10 ton of In, the *pp* and ^{7}*Be* neutrinos are clearly measured
- ~2000 *pp* events

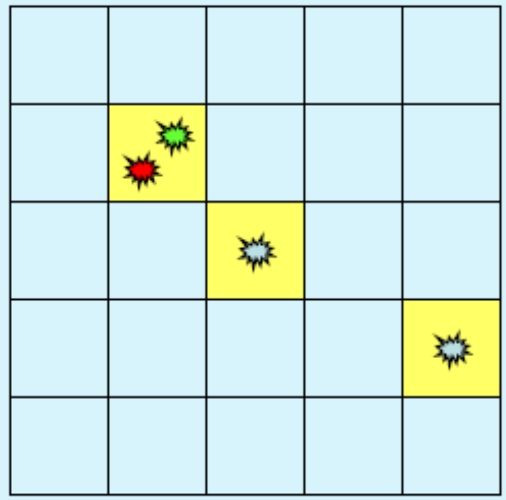


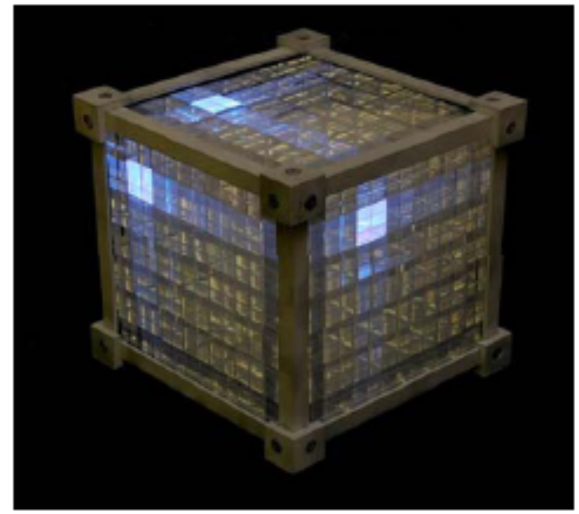
signal electron energy [MeV]

LENS Novel Lattice Readout

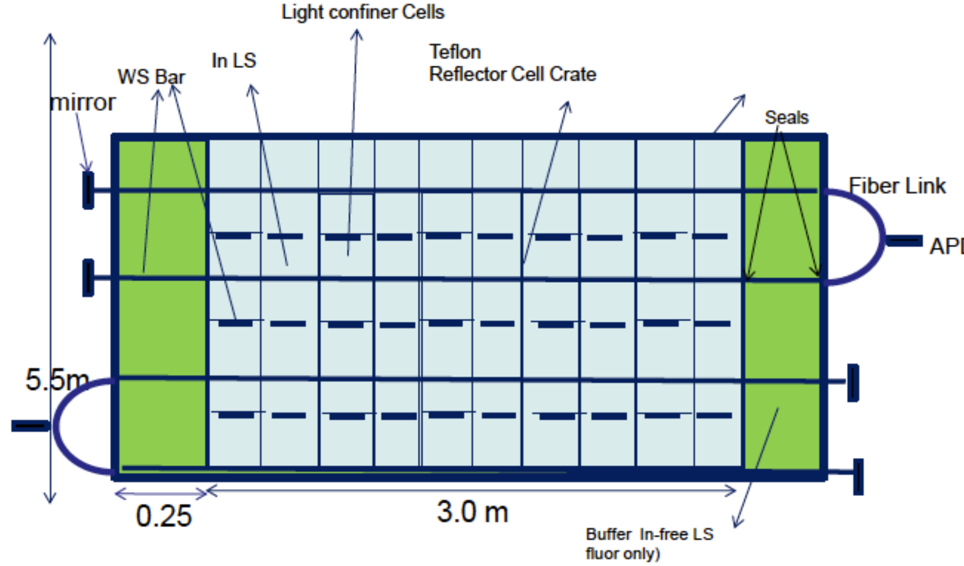
Signal







Lens NUFlu Chamber—3.5m3.5mx5.5m (including side buffer--~10 ton Indium



even newer readout idea under R&D

LENS Yb

- LENS had a brief life as a ytterbium-loaded liquid scintillator but the 50 ns plus 5.3 hr tags proved challenging
- ^{176}Yb is a ββ isotope

Q-value = 1.08 MeV

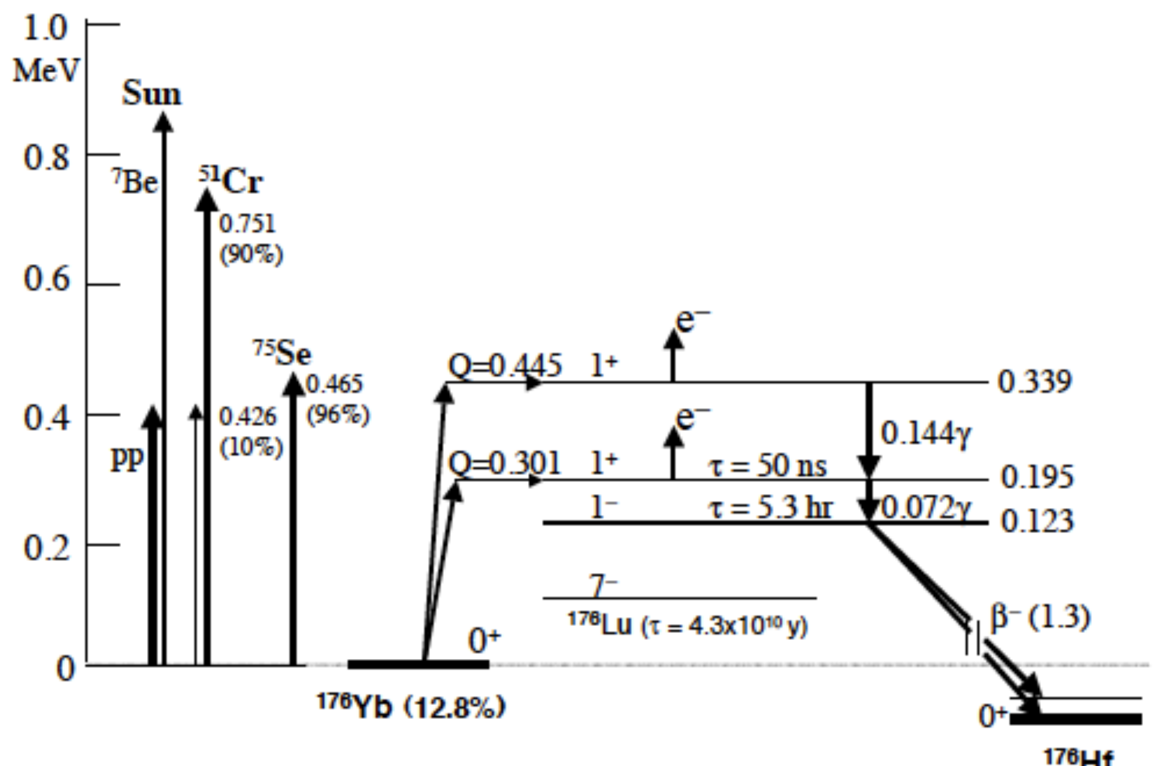


Fig. 1 Yb-Lu LENS: Levels and Tags

^{100}Mo as a Solar Neutrino Target

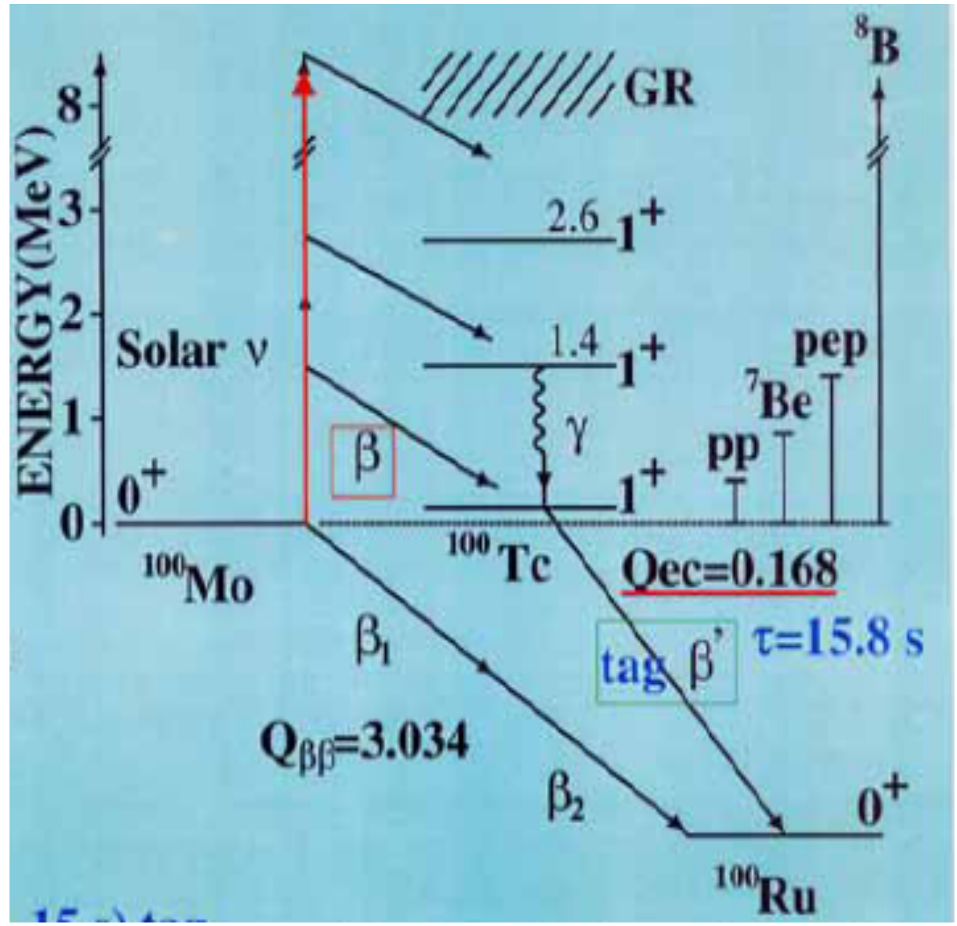
$$\nu_e + {}^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Tc} + e^-$$

$$ {}^{100}\mathrm{Tc} \rightarrow {}^{100}\mathrm{Ru} + e^- + \bar{\nu}_e$$

just like ^{176}Yb, this is another instance of a double beta isotope serving as a solar neutrino target

0.168 MeV threshold for CC ν_e
^{100}Tc beta decay: 15.8 s lifetime

tagged solar neutrino sensitive to *pp*



MOON – Molybdenum Observatory Of Neutrinos

- CC measurement of *pp* flux using Mo target foils
  - $\nu_e + {}^{100}Mo \rightarrow {}^{100}Tc + e^-$ (threshold 168 keV)
  - ${}^{100}Tc$ β decays with 16 s half-life, Q = 3.0 MeV
- has background from $2\nu\beta\beta$ of ${}^{100}Mo$

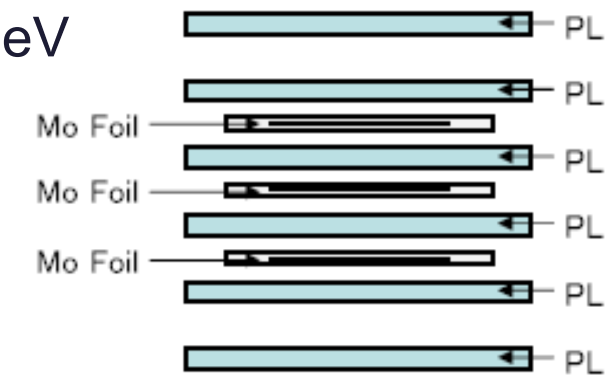
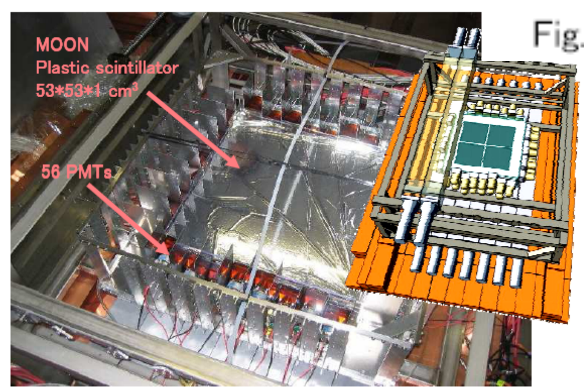


Fig. Cross section view of MOON-1

Reaction	Rate/yr/ton ^{100}Mo
pp	120
^{7}Be	40
pep	2.5
^{8}B	5.1
^{13}N	4.2
^{15}O	6.1

9.6% natural isotopic abundance



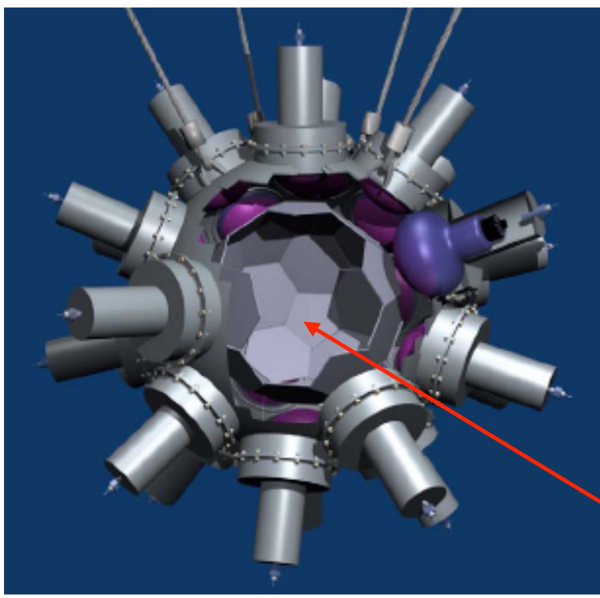
MOON-1 prototype
142 g of ^{100}Mo foil
40 mg/cm^2

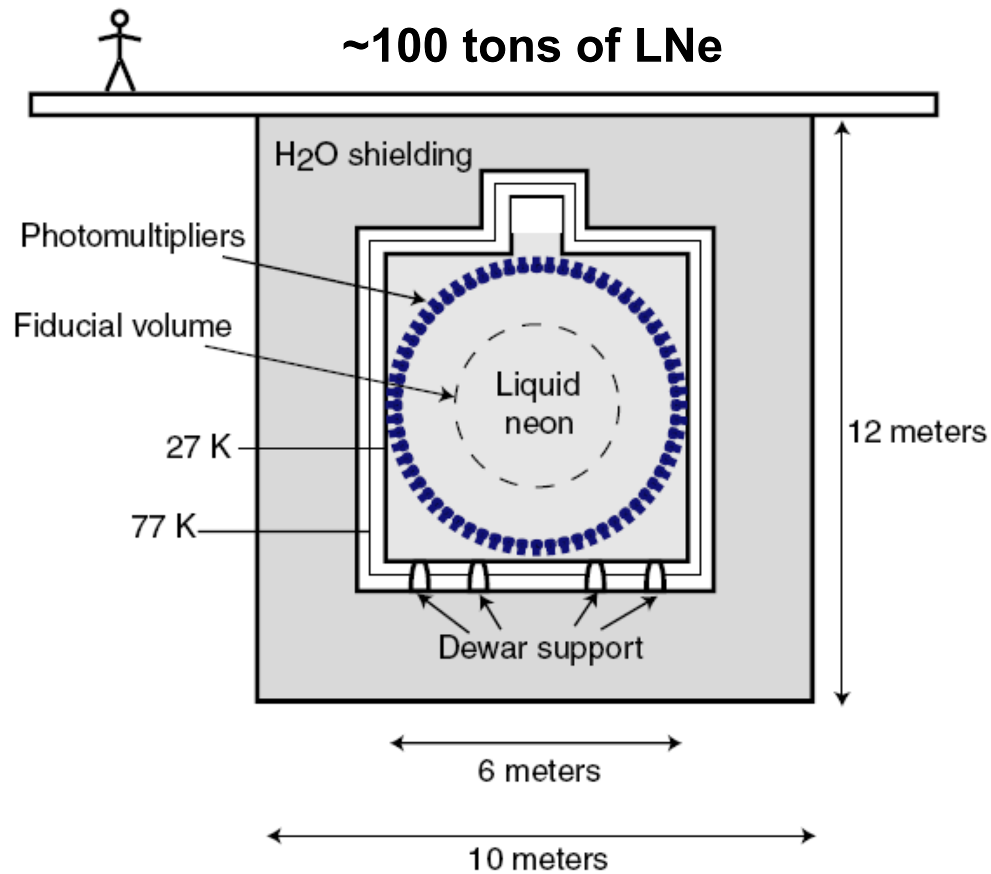
Elastic Scattering Experiments: CLEAN and XMASS

- ν-e scattering in liquid noble scintillator to detect *pp* solar neutrinos
- these are dual purpose detectors: dark matter and solar ν
  - XMASS also double beta decay of ^{136}Xe
- oscillated event rate: ~1 *pp* ν event/(day·ton) for 50 keV threshold
- main detector concept behind each experiment
  - CLEAN: liquid neon has no radioactive contamination
  - XMASS: liquid xenon has very effective self-shielding

CLEAN – Cryogenic Low Energy Astrophysics with Neon

- building Mini-CLEAN a 100 kg prototype dark matter detector with LNe/ Lar in SNOLAB

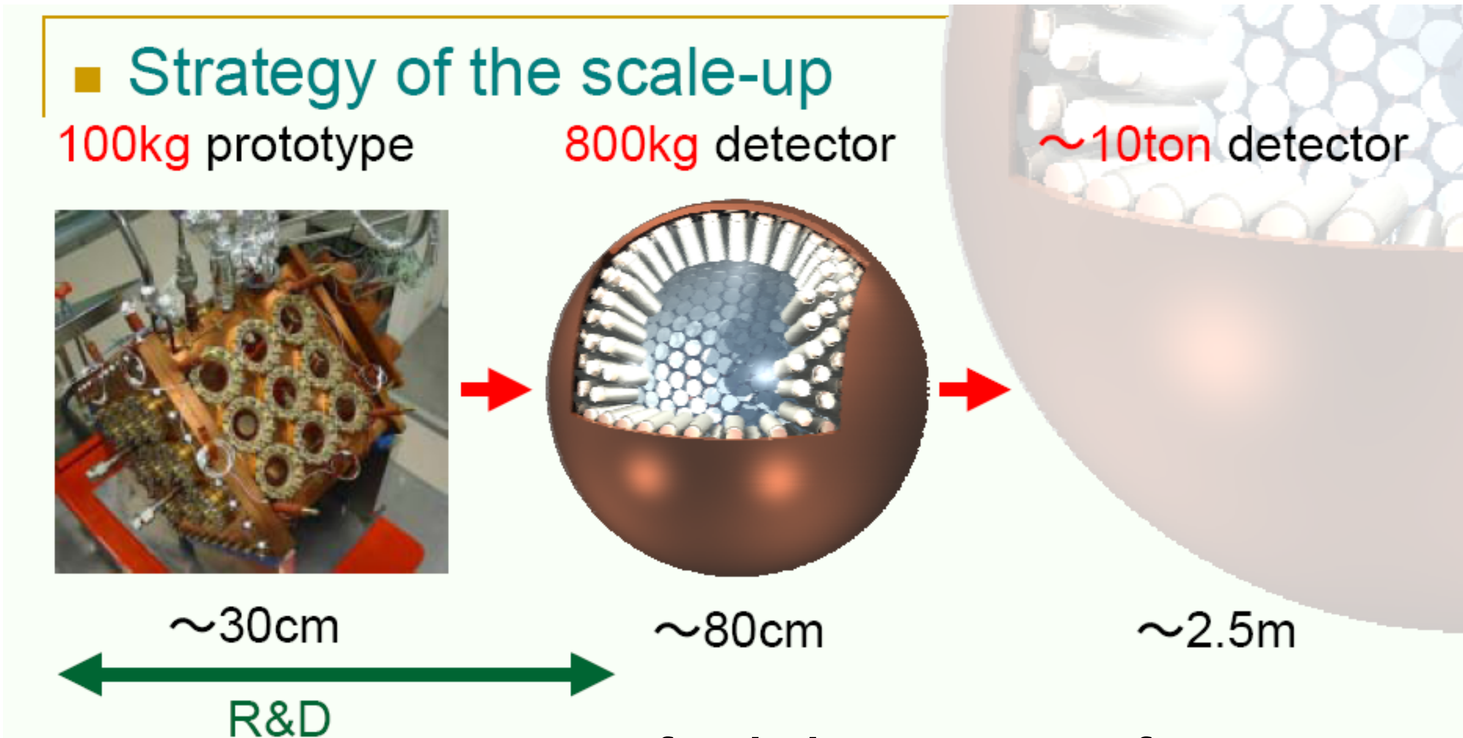




50 cm diameter

XMASS – Xenon MASSive Detector

- 100 kg prototype built, operated, studied
- soon turning on 800 kg detector for dark matter
- *pp* solar neutrinos require 10 ton fiducial volume and even larger size for self-shielding



for dark matter

for *pp* solar n

SNO+ is Under Construction

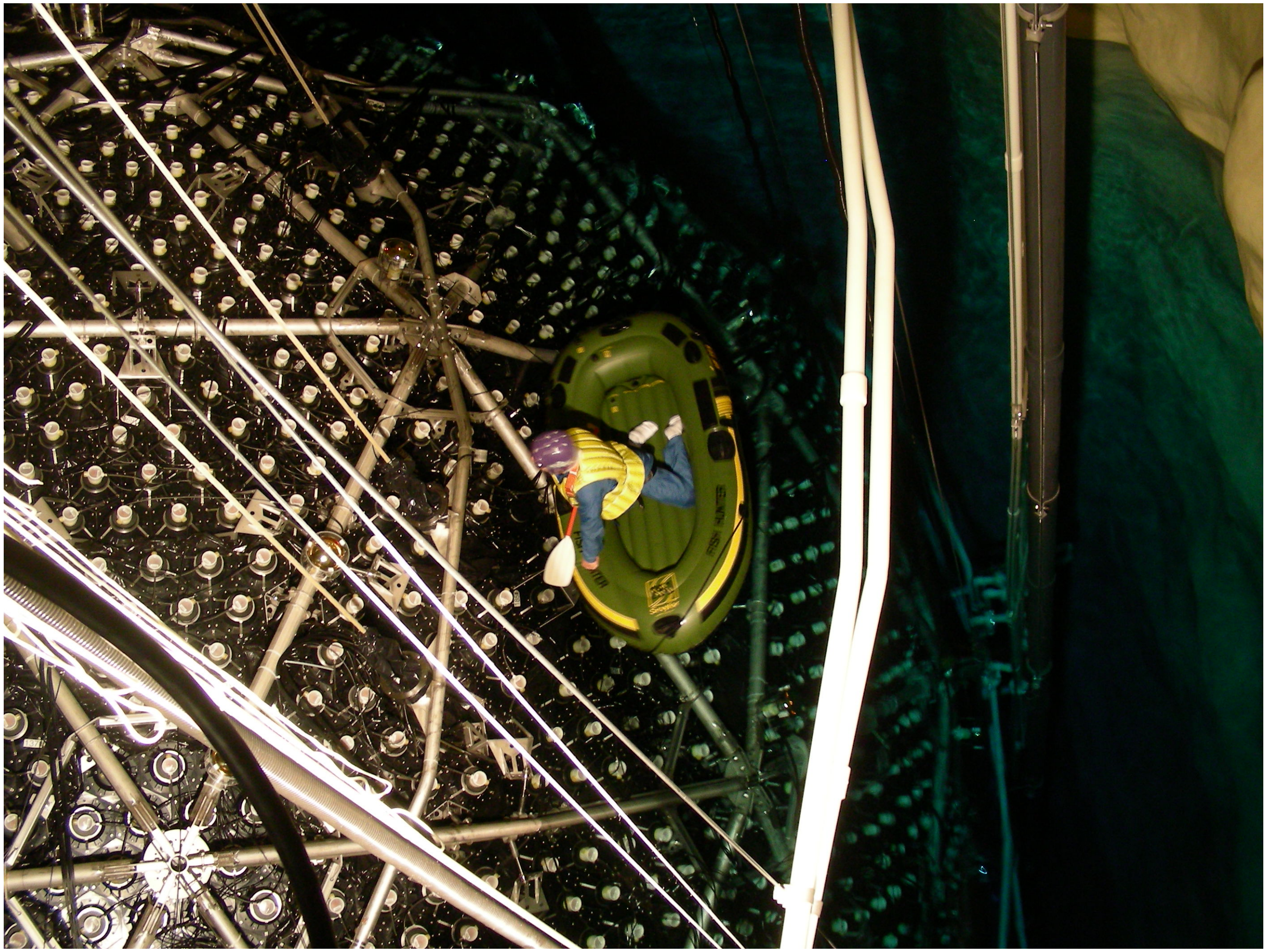
- in my remaining time, I will show photos and describe the status of SNO+ construction
- and I will show photos of SNOLAB (the expanded underground laboratory for new experiments in neutrino physics, dark matter, double beta decay)

Turning SNO into SNO+

- to do this we need to:
  - buy the liquid scintillator
  - install hold down ropes for the acrylic vessel
  - build a liquid scintillator purification system
  - make a few small repairs
  - minor upgrades to the cover gas
  - minor upgrades to the DAQ/electronics
  - change the calibration system and sources

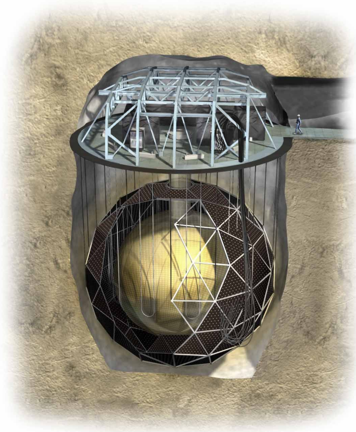
a new experiment with new and diverse science goals, for modest cost

Draining SNO and Boating Inspections



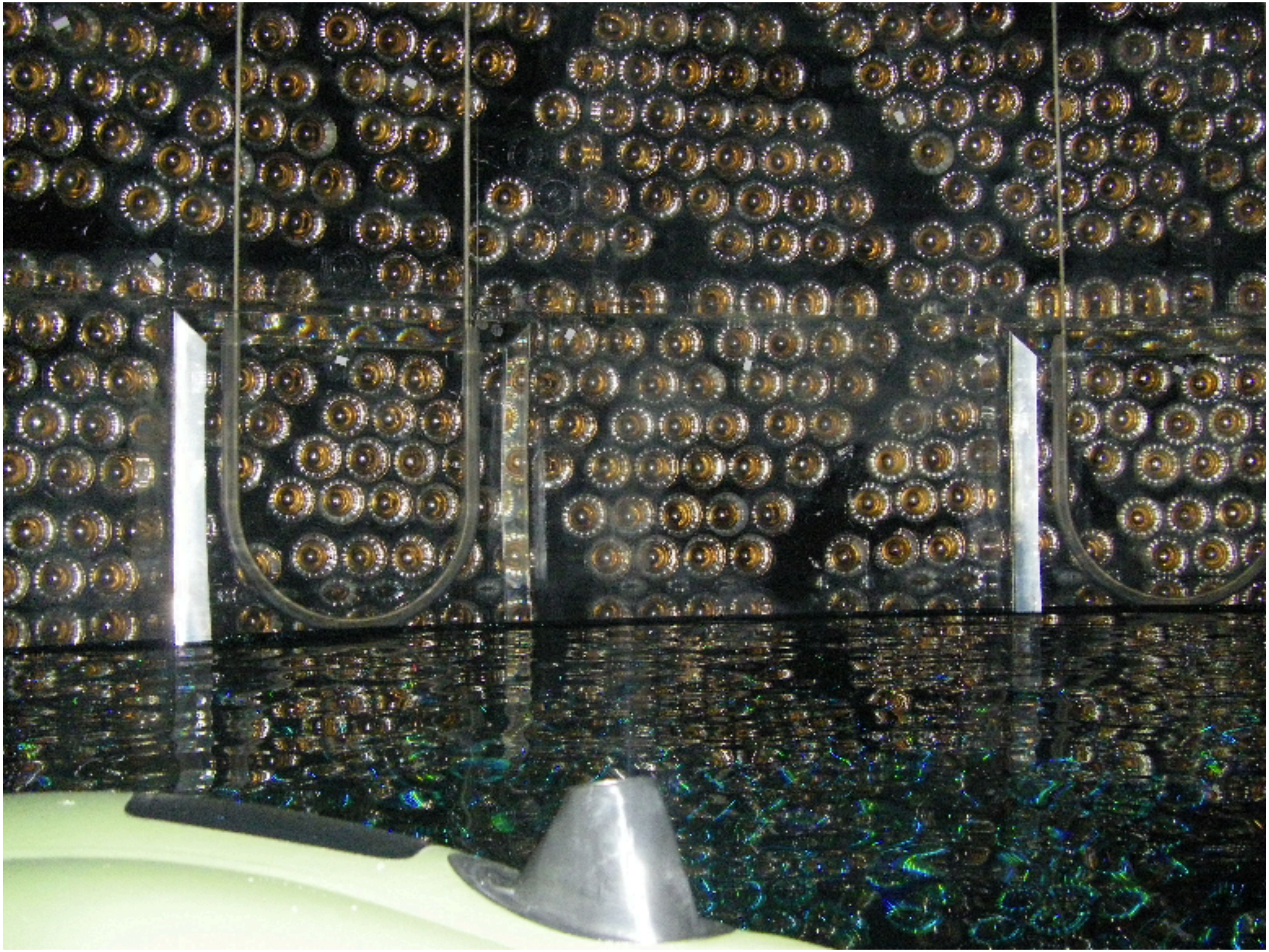
Inside AV Boating

no crazing or deterioration of acrylic seen

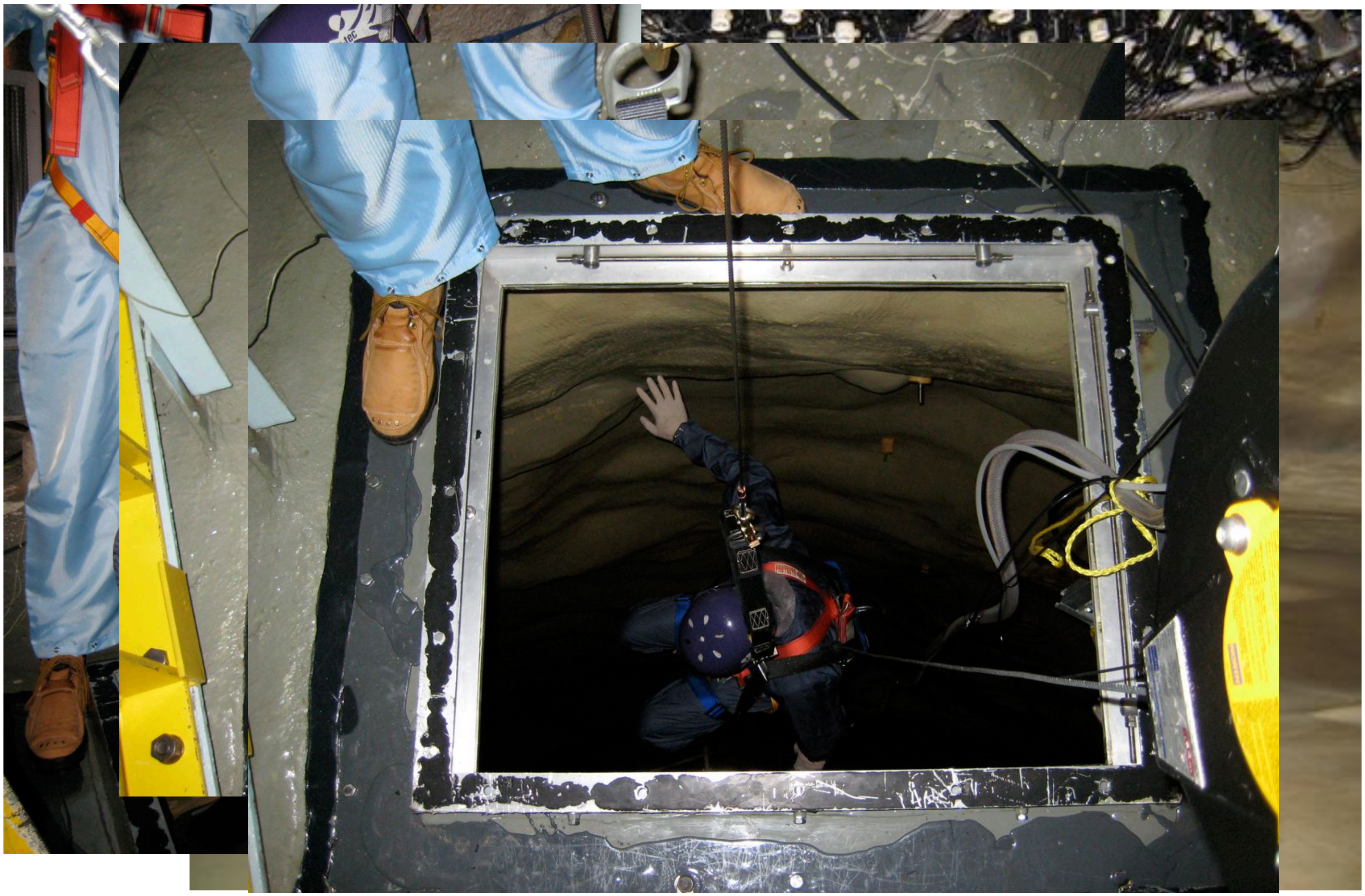


- boating has taken place *inside* the acrylic vessel
  - to attach survey targets
  - inspection for engineering re-certification
- many inspections in the outer detector and cavity

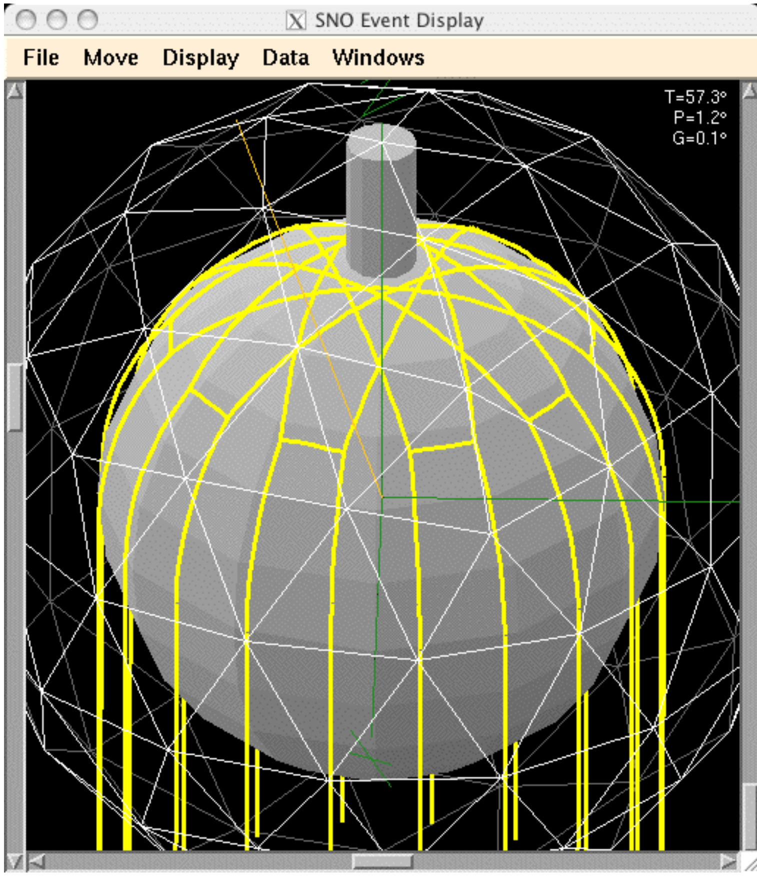
outside PSUP boating



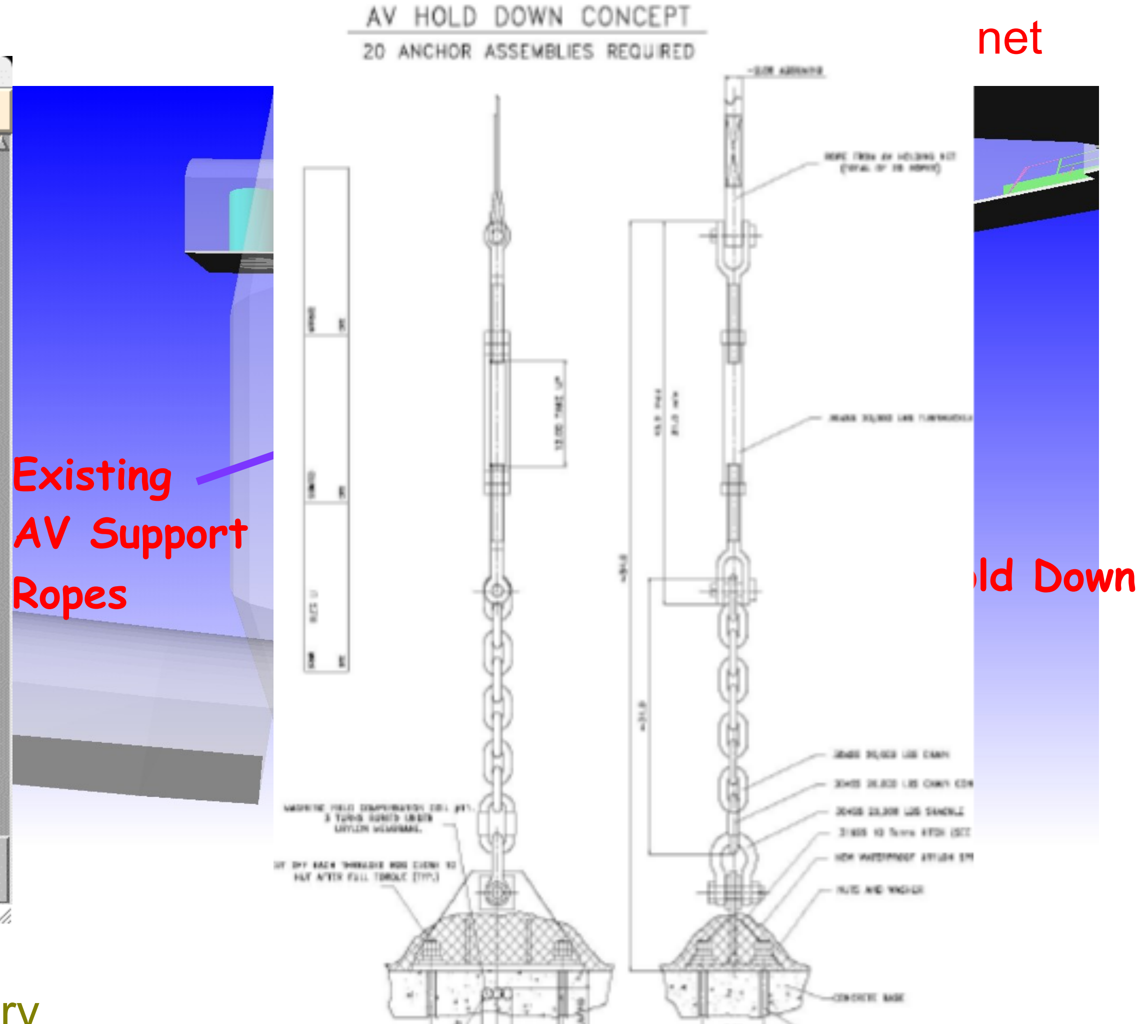
Entering the SNO Cavity – Inspections



SNO+ Rope Hold Down Net

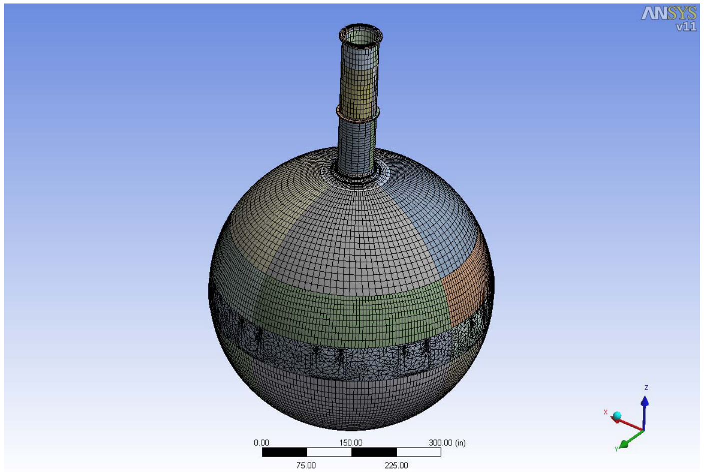


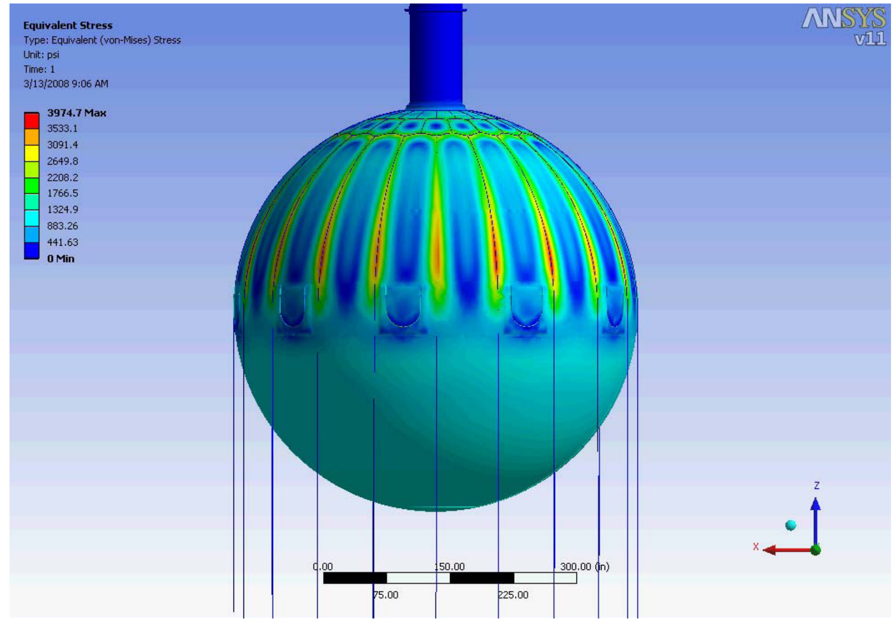
rope tension calculation and
visualization of net-PSUP geometry

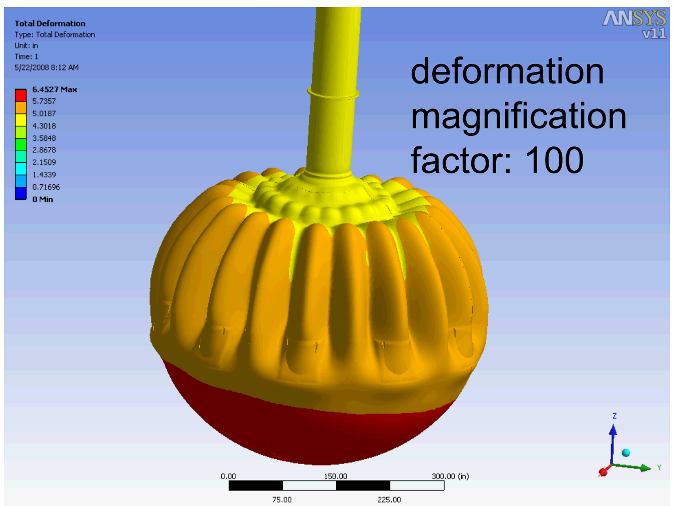


SNO+ ropes will be Tensylon: low U, Th, K ultra-high molecular weight polyethylene

Buckling and Finite Element Analysis



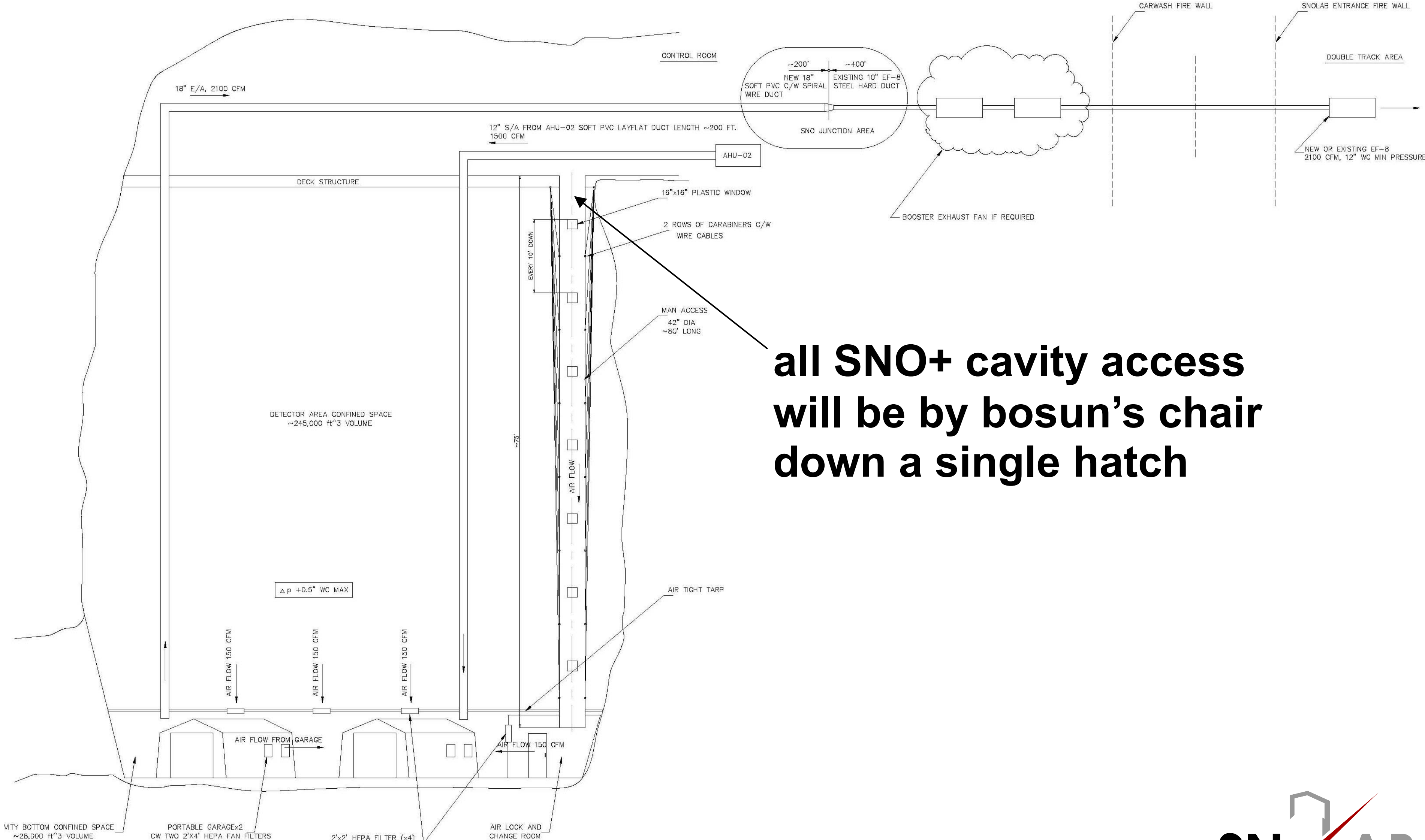




- stresses below SNO limit of 600 psi
- considered extreme case with **empty AV** surrounded by water outside: **does not buckle**

AIR HANDLING FLOWSHEET

(see drawing # SLDO-SNP-FL-2001-01)



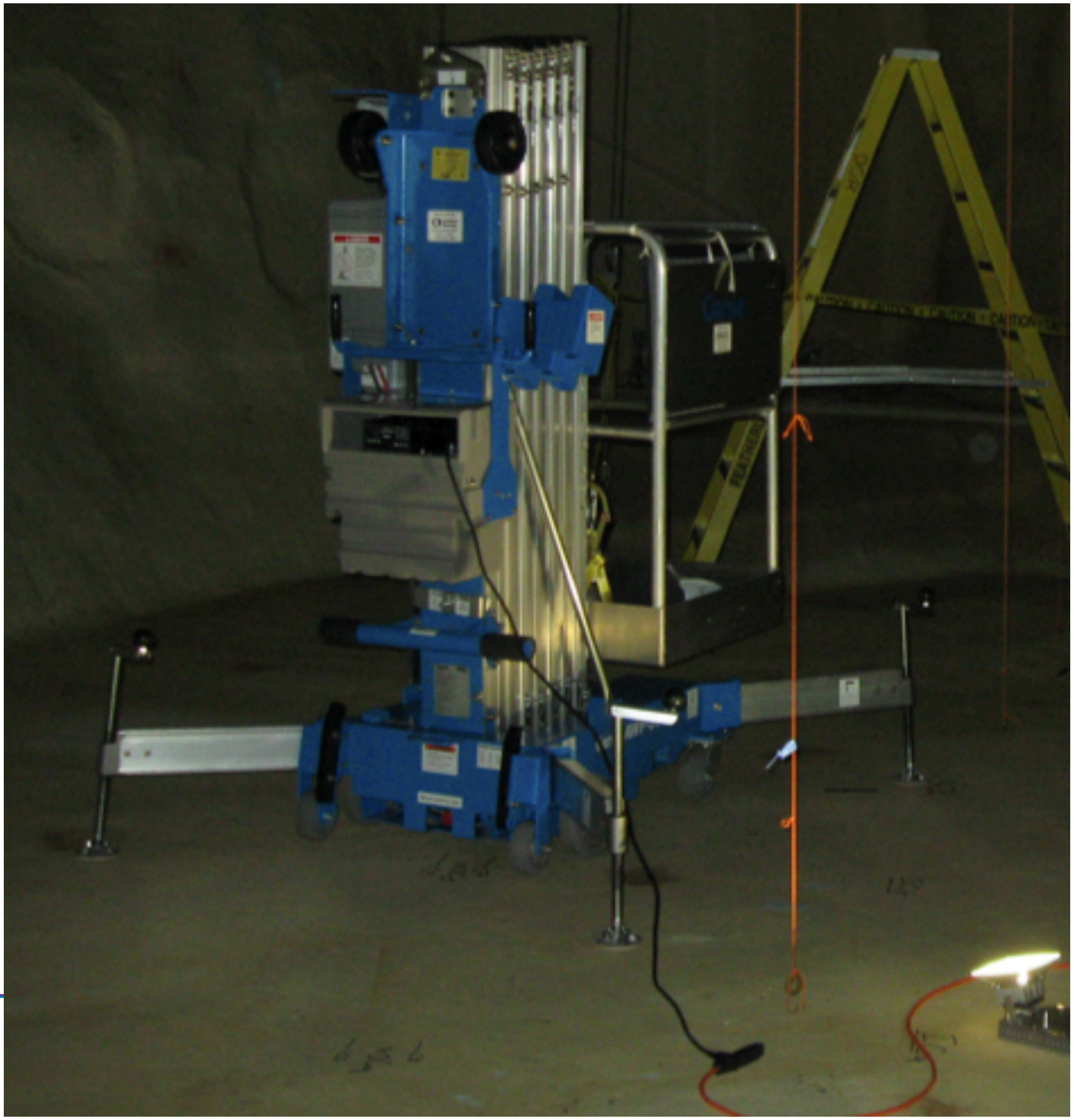
all SNO+ cavity access will be by bosun's chair down a single hatch

Status of SNO+ Construction

- SNO+ is fully funded and proceeding with construction
- major construction work in the cavity is beginning
- scintillator purification system ordered, designed and being built; installation in Fall 2011
- SNO+ has broken ground in the utility room...
  - the scintillator purification system requires the enlarging of the old "D2O pit"
- some "dead" SNO PMTs are being removed, repaired, and replaced
  - it's not planned to repair all dead SNO PMTs; rather, while we have time, those easiest to access, we have found are easy to repair

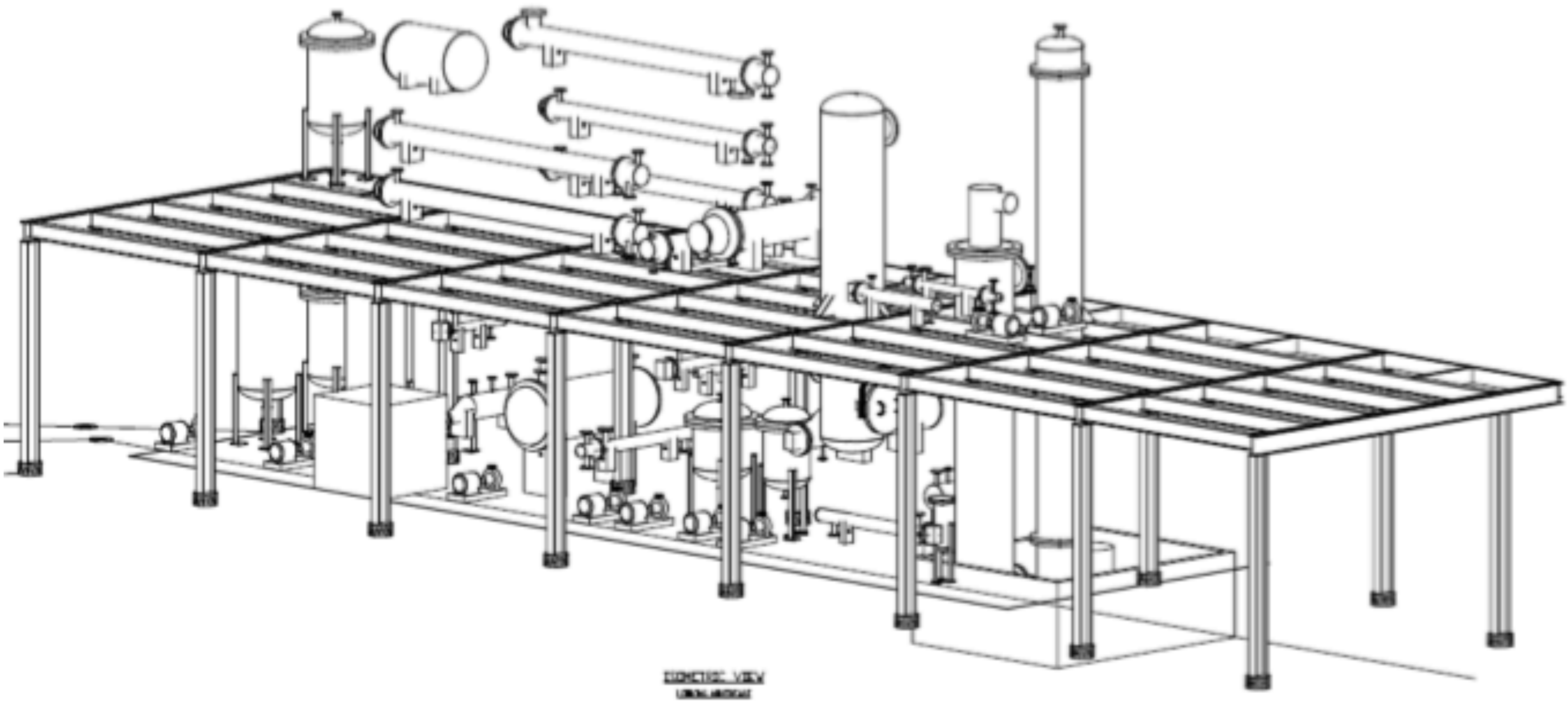
Genie Lift in the Cavity

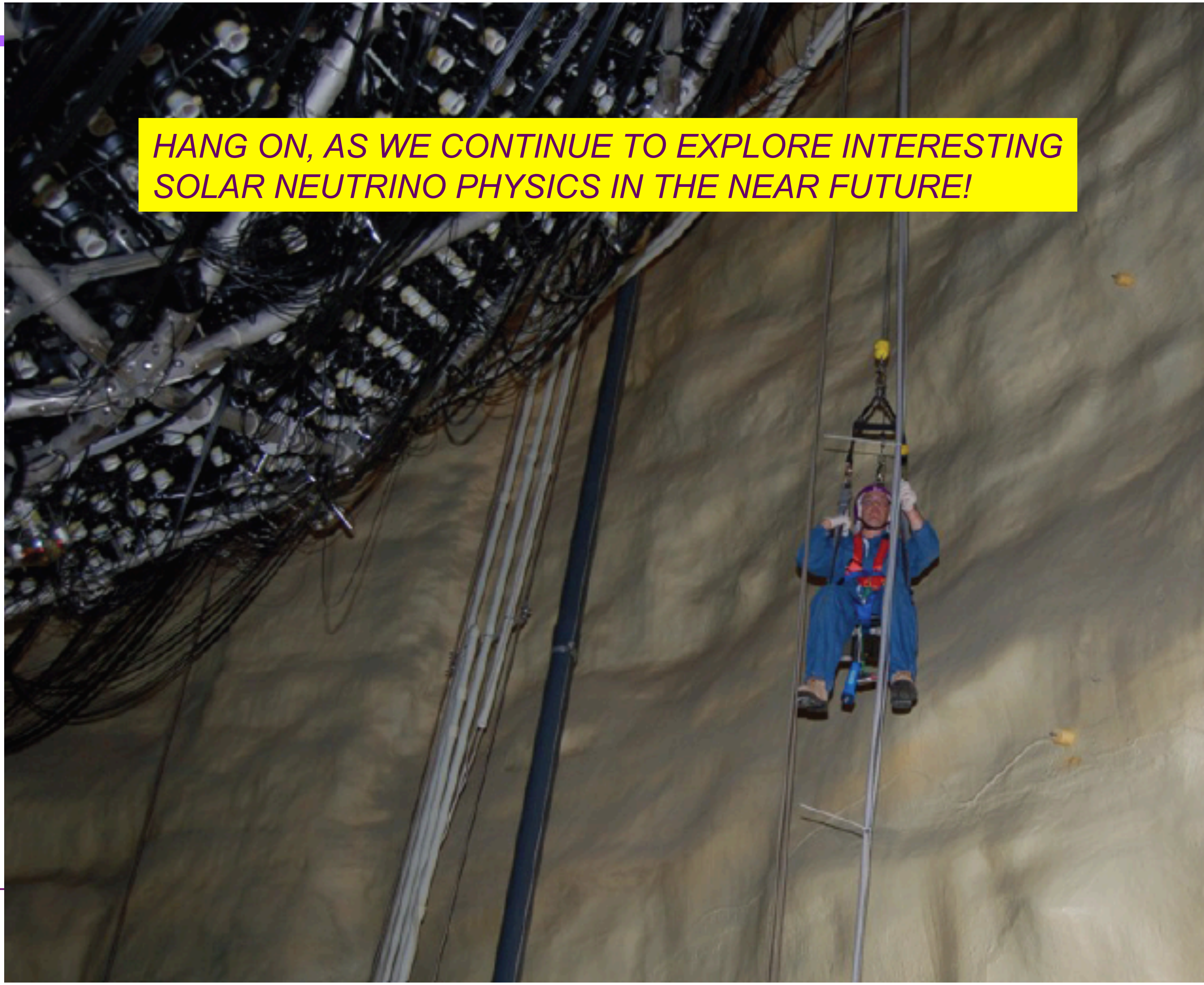
- for accessing PMTs and modifications of the PMT support structure



Scintillator Purification and Process Systems

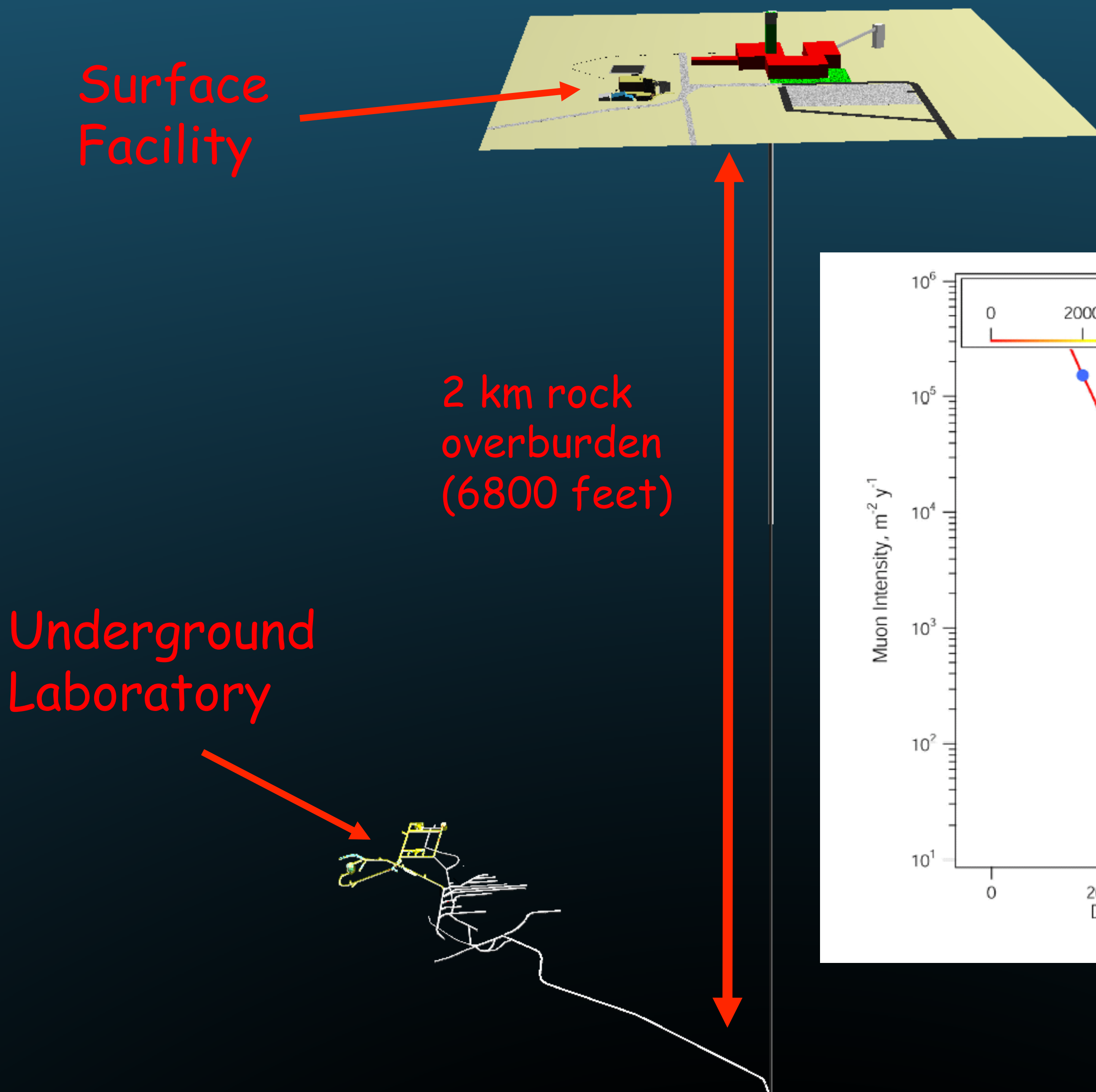
- *designed by KMPS (who designed/built Borexino scintillator purification)*
- *purification system pit excavation underway*

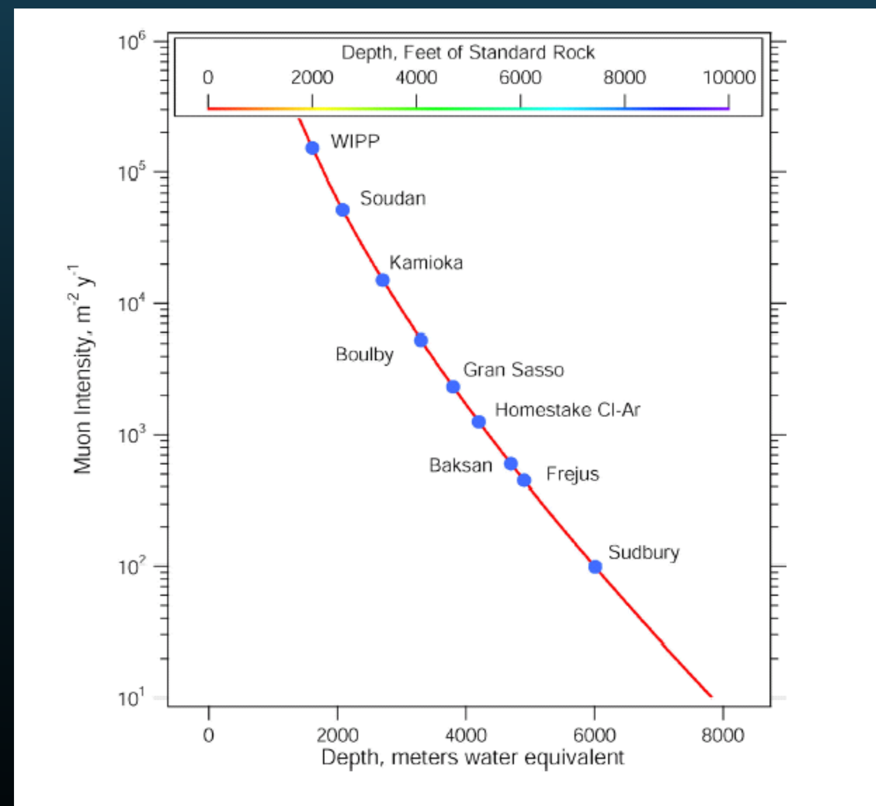



HANG ON, AS WE CONTINUE TO EXPLORE INTERESTING
SOLAR NEUTRINO PHYSICS IN THE NEAR FUTURE!

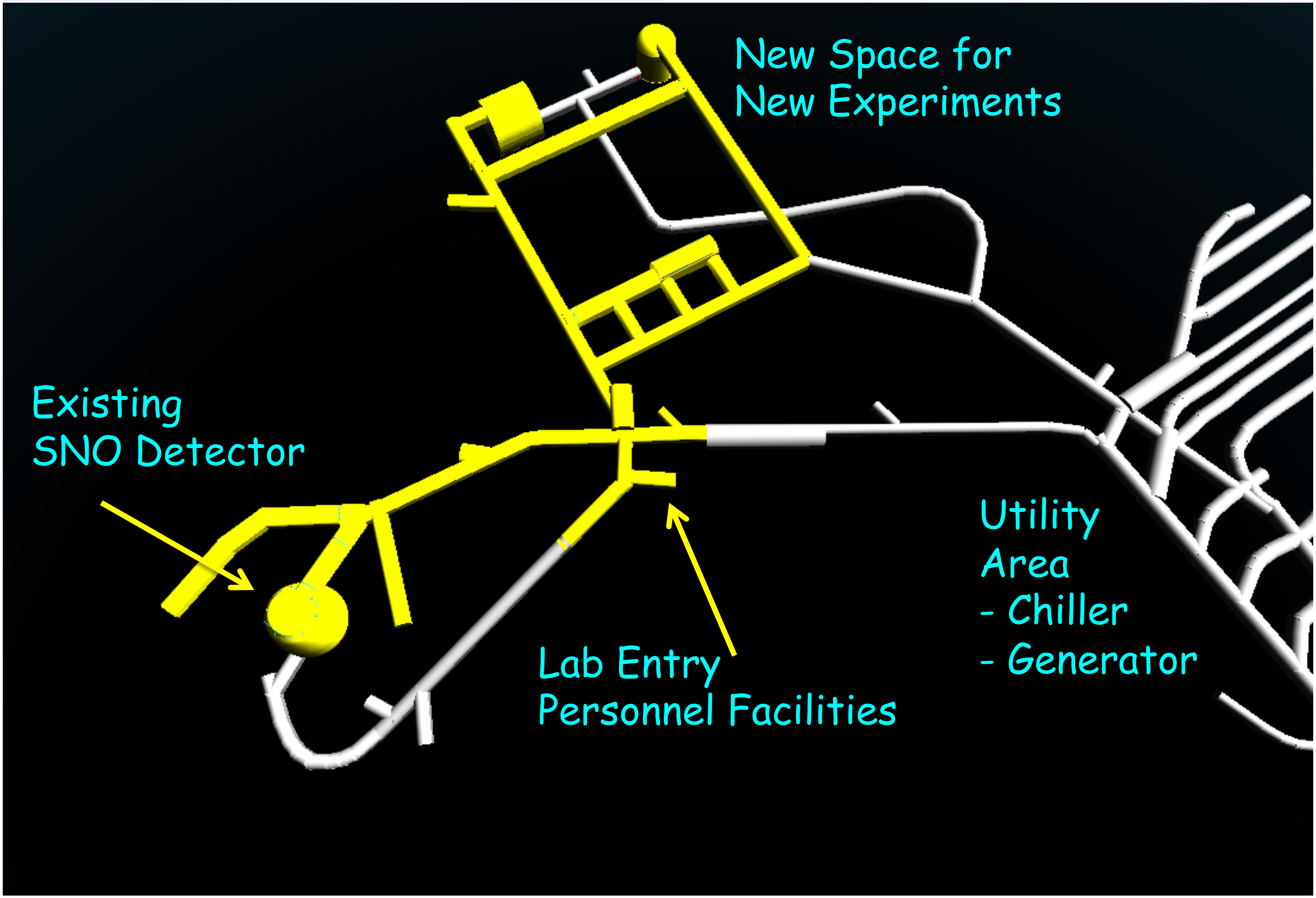
SNOLAB Slide Show

SNOLAB


Surface Facility
2 km rock overburden (6800 feet)
Underground Laboratory

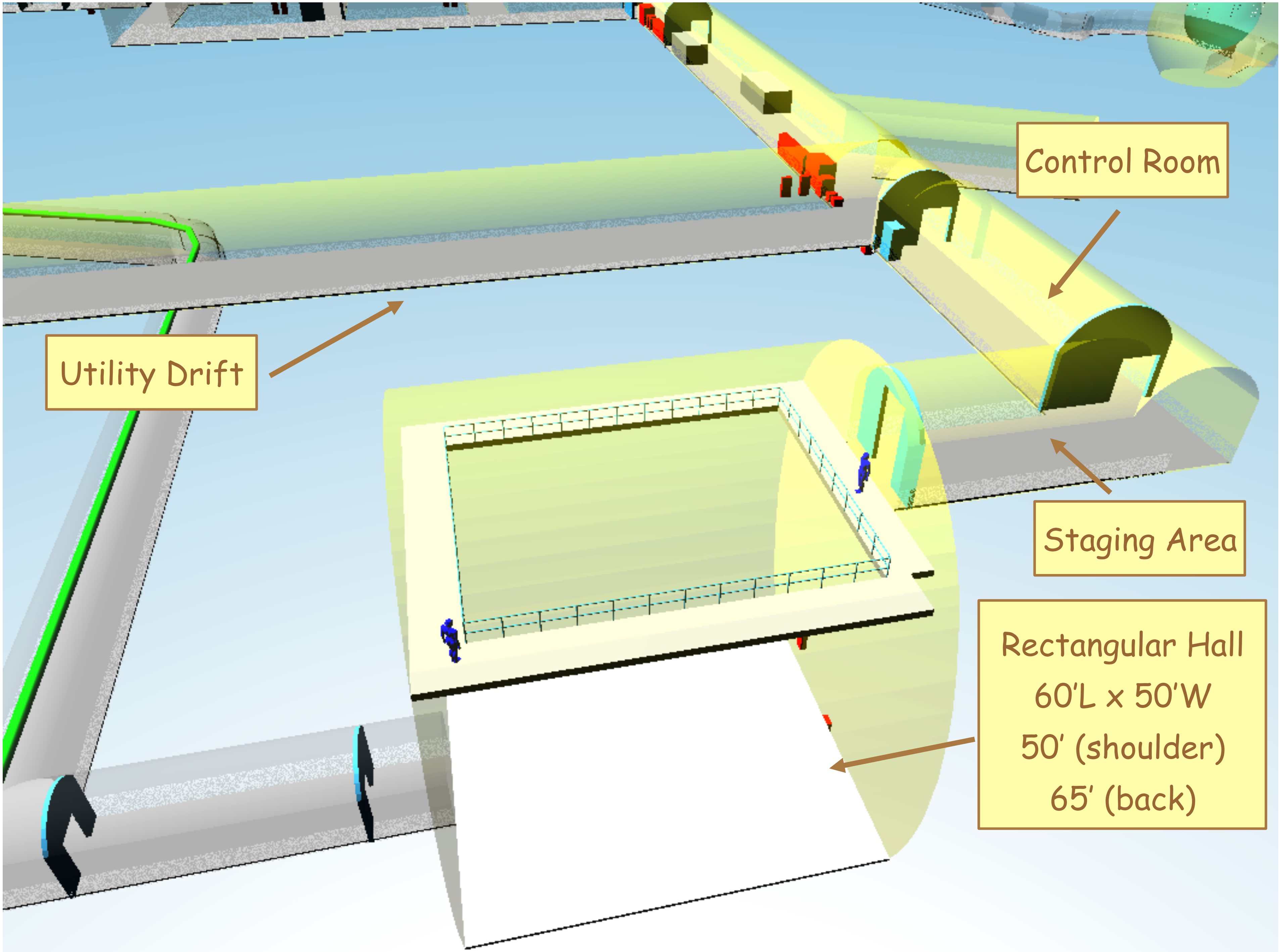

Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
Muon Intensity, m^{-2} y^{-1}
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
Depth, meters water equivalent

SNOLAB


New Space for
New Experiments
Existing
SNO Detector
Lab Entry
Personnel Facilities
Utility
Area
- Chiller
- Generator

SNOLAB Surface Building

SNOLAB Excavation



Control Room
Utility Drift
Staging Area
Rectangular Hall
60'L x 50'W
50' (shoulder)
65' (back)


Lab Entry
SNO
LAB
AAF

Lab Entry


Lab Entry
FEATHERLITE.CA


Lab Entry


Personnel
Area


Personnel
Area


Hall Bottom
Access


Ladder Labs


Cube Hall


Cube Hall